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Comparative cost analysis of foundations and base floor structures in small wooden houses

Master of Science thesis

Sibbo, 22.5.2017
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Sammanfattning av diplomarbete

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Sammanfattning

Grunder och bottenbjälkslag är bland de viktigaste konstruktionsdelarna i ett småhus. För att ett hus skall vara säkert och hälsosamt att bo i finns det obligatoriska funktioner, som måste uppfyllas och krävs av myndigheterna. Grunden och bottenbjälkslaget fungerar som en helhet och skall därför planeras tillsammans. Det finns många olika byggnadssätt med vilka man kan åstadkomma de krävda funktionerna som är reglerade.

Målet med detta forskningsprojekt är att utveckla en modell som kan ligga till grund för att välja de mest kostnadseffektiva alternativen för grund och bottenbjälkslag i småhus byggda av trä. Modellen kommer att bygga på kostnadsjämförelser mellan olika möjliga alternativ.

De obligatoriska funktionerna som har kartlagts är följande: tillräcklig hållfasthet och stabilitet; undvikande av tjälskador; fuktsäkerhet; skydd mot radongas; och tillräcklig energieffektivitet. De olika funktionerna har analyserats och olika alternativ för att uppfylla dessa funktioner har undersökts.

De olika konstruktionalternativen har inledningsvis designats så att de uppfyller sin funktion på ett tillfredsställande sätt. Därefter har de olika alternativen kunnat jämföras enbart på basis av kostnadseffektivitet. För att kunna genomföra studien på ett logiskt sätt, har tekniker som härstammar från värdeanalys använts.

Resultaten påvisar vikten av att undersöka byggplatser noggrannt innan köp, för att säkerställa att grundberget inte ligger alldeles vid markytan. Detta är centralt eftersom grundläggningskostnaderna alltid tenderar att stiga då berget ligger nära markytan. I detta projekt framkommer dessutom att det på tomter med god grundbotten lönar sig att endast använda platta på mark som bottenbjälkslagskonstruktion, istället för självbärande konstruktioner. Därtill visar resultaten på att träbottenbjälkslag skall undvikas, eftersom det för med sig en betydligt högre kostnad.

Nyckelord Värdeanalys, kostnadskalkyl, bottenbjälkslag, grund, småhus

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Abstract of master's thesis

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Abstract

Foundations and base floors are among the most important building parts in a small house. In order to be a safe and healthy house to live in, there are mandatory functions demanded by authorities that have to be fulfilled. The foundation and base floor work as a unity and thus have to be designed together. Many different structural alternatives fulfill the mandatory functions that are given in the regulations.

The objective of this research project is to develop a model, by which the most cost-efficient foundation and base-floor solution for small wooden houses can be chosen, among different functional solution alternatives. The model will be based on cost comparisons between different alternative solutions.

First, the mandatory functions have been mapped, and they are sufficient with respect to strength and stability, avoidance of damages by ground frost, moisture control, radon gas control, and energy efficiency. Secondly, each function has been examined and different methods to fulfill the functionality of the structures have been explored.

All of the structural alternatives have been designed in order to fulfill the functions in a sufficient way. Thereby it is possible to compare them according to cost-efficiency solely. To be able conduct this study in a logical way, a value engineering approach has been applied.

The results show that before acquiring a building lot, it is of great significance to investigate if the bedrock is close to the ground surface. Bedrock at the surface always increases the cost of foundations and base floors. Further, it has been demonstrated that on firm soil, only ground supported base floors should be used, instead of using self-supported base floor structures. In addition, it has been clarified that wooden base floors should be avoided, due to a considerable higher cost.

Keywords Value engineering, cost-analysis, base floor, foundation, small house

Preface

The choice for this thesis topic was result of my personal thoughts about which foundation and base floor solution that is the most cost-efficient one. I have taken part in many small house projects where the solutions have been different even if the preexisting conditions have been the same. This experience and the will to find the most cost-efficient solutions, when I am now designing my own home, led me to this topic.

I want to thank my supervisor and instructor Professor Antti Peltokorpi for an objective and accommodating manner in supervising this thesis process. I also want to thank my sister for proofreading my thesis.

Sibbo, 22.5.2017

Jaan-Otto Bäckblom

Contents

Abbreviations

CFG	Concrete floor on ground
EPS	Expanded polystyrene
HCS	Hollow-core slab
LWA	Light-weight clay aggregate
LWC	Light-weight concrete
ROK 2016	Rakennusosien kustannukset 2016 (Cost of building elements 2016)
VE	Value-engineering
XPS	Extruded polystyrene

1 Introduction

1.1 Background information

All small houses have a foundation and a base floor. Historically, foundations have been made out of natural stone and concrete. During the 19th and in the beginning of the 20th century small house foundations consisted only of natural stone piled directly on the ground or of a hole filled with stone and the base floor was only insulated with soil (Hemgren, 1998). The foundation and base floor structures have developed a lot during the past 100 years and they are today much more complicated structures than before due to higher demands on e.g. energy efficiency, comfort, stability, and longer lifetime.

According to Hemgren (1998) the foundation has five functions:

1. It shall establish a stable base to the house frame and not be able to move due to ground frost or settlements in the ground.
2. It must keep the house dry to avoid damages by moisture.
3. It must protect the house from energy loss due to lower temperatures outside the house.
4. Importance to the outside appearance.
5. It has to protect the house from radon gas seeping into the indoor air.

From a technical functionality perspective, points number 1, 2, 3, and 5 are of most importance. The appearance is of course often significant but from a technical research point of view, it is of a minor importance. The base floor and foundation structure are always connected to each other and have to be chosen at the same time, thus they should be observed as a whole (Siikanen, 1998). By observing them as a unity, the same functions can be applied for the base floor and the foundation, respectively. The function of aesthetical importance is an exception, as the base floor structure is typically visible from neither the outside nor the inside of the house.

Small house market is remarkable part of the economy. In 2016, the Finnish residential housing construction market had a value of 5.7 billion Euros and a volume of 12.5 million cubic meters of residential housing (Rakennusteollisuus RT, 2017). The small house or houses built with small-house technique (row-houses) amounts to 45% of the residential construction volume (Rakennusteollisuus RT, 2017). If the assumption is made that the cost per cubic meter is the same in small house as in high-rise residential buildings, the value of the small house market could be roughly estimated to have been equivalent to 2.6 billion Euros in 2016.

Foundations and base floors are an economically remarkable part of the building investment. According to Nissinen and Koskenvesa (2004) the cost of excavation for and construction of a foundation amount to 10-16% of the total construction cost for a small house. Consequently, the value of the small house foundation market could have been as much as 0.4 billion Euros in 2016. Even though the cost of base floors is not included in this estimate, it pictures the magnitude of the market that is under scrutiny in this research project.

1.2 Problem description

Many different solutions are provided for constructing a functional foundation and base floor structure. As mentioned above, the base floor and foundation are always connected to each other and should be observed as a whole. This raises the question concerning how these structural solutions should be chosen, in order to achieve the best cost-efficiency. Is there a read tread or rule of thumb that could be used in decision making to achieve the most cost-efficient solution, yet a functioning solution?

There are many different opinions about what is the best solution for these structures. The reasoning behind different opinions can be based on assumptions about cost, stability, moisture performance, energy efficiency etc. The natural characteristics of the building lot are also a source of opinions concerning its impact on the structure and cost. Some experts argue that a lot with a high natural bed-rock level will cumulate more cost than a lot without high bed-rock but still load bearing soil (Kupiainen, 2016). How do the primary circumstances of the building lot affect the construction cost, does the appearance of bedrock in the surface have a significant impact on cost?

In fact, several structural solutions fulfill the mandatory functions of a foundation and base floor. If the mandatory functions are fulfilled, the cost differences should be the only matter of interest left in the selection process. By utilizing value engineering, that is examining the ratio of function to cost (Atabay and Galipogullari, 2013), a method to assist the selection of the most cost-effective solution could be found. This method should be based on objective facts rather than assumptions and opinions.

1.3 Objective

The objective of this research project is to develop a model by which the most cost-efficient foundation and base-floor solution for small wooden houses can be chosen among different functional solution alternatives.

The model will be based on a comparative cost-analysis. Furthermore, the model will be tested on a case building in order to analyze if the model creates reliable information or if there are reasons to change or improve the present model for choosing foundation and base-floor structures. The model could be used when the building lot is already acquired, as well as for evaluating different building lot alternatives prior to acquirement.

1.4 Research method

The study begins with a literature review. First, the value engineering process, which different phases will lead to the final comparative cost-analysis, will be presented. All other chapters in this study will be parts in the value engineering process. Second, the Finnish legal regulations that decide mandatory demands regarding foundations and base-floors will be mapped and examined. Third, the different strains that foundations and base-floors are exposed to, such as loads and building physical phenomenon, will be examined. Further, different solutions for achieving certain functionalities will be presented. Fourth, different structural solutions that fulfill the functionally demands will be demonstrated. Further, the comparative cost-analysis will be executed on these different solutions by the comparing the cost of different alternatives.

The cost-calculations will be done in excel utilizing its possibility to calculate large numbers of data and the capability to easily changing input data when comparing cost. The cost data will be taken from reliable empirical cost data from branch literature based on construction in Finland. Cost data not found in the literature is obtained through interviews with appropriate contractors in the specific branch. The influence of different parameters on the final cost, such as climate zone, and foundation depth, will be examined as well.

Finally, the model is tested on a case houses that are situated in southern Finland. Then the results of the test will be evaluated and conclusions will be drawn about the reliability of the model and whether the current approach of structural selection process is cost-effective.

1.5 Scope and limitations

This study has limited its scope to small wooden houses that are houses in which the main load bearing structures of the superstructure are made out of wood. This choice is made because wood is a very popular construction material in small houses and is a relatively light construction material compared to concrete and masonry. Thus, the load bearing capacity of the foundation is not a decisive factor when comparing structures in this study. Usually small houses only have 1, 1.5 or 2 stores, and therefore the study will be limited to buildings this size.

The building lot characteristics are limited to lots with good load bearing capacity or bedrock. Thus, pile-foundations for lots with weak bearing capacity are not examined in this study. Basement foundations are not examined either.

The study will be set in the geographical area of southern Finland, with corresponding climate. Nevertheless, the model could be utilized in areas with similar climate if input cost data is changed accordingly. The mandatory building regulations in Finland will applied for the structures. The thermal insulation in the base floor will set as the minimum requirement for energy efficiency in Finland for year 2016. Only commonly used building materials will be examined, in order to ensure reliable cost-data. The cost that will be examined is for the whole foundation structure with fillings and the base floor structure from floor slab downwards. No finishing materials will be analyzed.

A normal building such as a small house, has the designed working life category of 50 years (SFS -EN 1990, 2006). Although the designed working life is 50 years it is recommended that the primary load bearing structures (foundations and framework) are designed one category higher, which in this case means 100 years (RIL 216-2013). This implies that foundations and base floors should be designed for at least the same lifespan as the building itself and will endure this time without more than normal maintenance and no essential repairs. Thus, the service cost will be low and thereby it will not be accounted for in the comparative cost-analysis. Instead the main focus will be on the initial investment cost.

2 Value engineering

2.1 History

Value engineering is a method applied in order to achieve better cost efficiency. It was originally developed during the Second World War. The method came up due to the material shortages during the war and because of the need to use substitute materials. It was a staff engineer called Lawrence D. Miles at General Electrics Company, who led an effort to create a methodical process to create value at a lower cost. This methodical process was called value engineering. (Mandelbaum & Reed, 2006).

Soon after, the private industry opened it eyes for the method, when they saw the possibilities to achieve better revenue, combined with the simplicity to perform the method (Mandelbaum & Reed, 2006). The method has since then been applied for reducing cost in many sectors, both for hardware and software, respectively (Atabay & Galipogullari, 2013). Furthermore, the method has been applied in the construction industry.

2.2 Definition of value engineering

Green (1994) defines VE as "A systematic procedure directed towards the achievement of required functions at least cost". Atabay and Galipogullari (2013) on the other hand, present a slightly more complicated definition: "An analysis of the functions of building etc., performed by a qualified agency or contractor personnel, directed at improving performance, reliability, quality, safety and life cycle cost". Finally, Mandelbaum and Reed (2006) define the concept as the following: "VE is an organized/systematic approach directed at analyzing the function of systems, equipment, facilities, services, and supplies for the purpose of achieving their essential functions at the lowest life-cycle cost consistent with required performance, reliability, quality, and safety".

Nevertheless, among the many different improvements mentioned by the definitions, cost reduction remains the main focus in VE. The other improvements mentioned can on the other hand be achieved by reducing the cost. Atabay and Galipogullari (2013) define value as the "ratio of functions to cost". Thereby, VE is regarded the process that is undertaken in order to create a better value at a lower cost. Importantly, the scope of VE is not solely cost reduction, as the functions of the object analyzed have to remain to improve the value (Mandelbaum & Reed, 2006).

$$\text{Value} = \frac{\text{Function (desired performance)}}{\text{Overall costs}}$$

Equation 1. The definition of value. (Atabay & Galipogullari, 2013).

2.3 VE in construction

According to Green (1994), VE is usually applied to projects in retrospective manner, in order to come to terms with budget overruns. Atabay and Galipogullari (2013), on the other hand, argue that VE should be executed as early as possible in the lifetime of a project. Both studies present valid points, as Green is proceeding from the situation of VE in construction on that specific time, whereas the other study theoretically explains when VE offers most advantages to cost reduction. In building projects, the cost is mostly defined during the early stages of a project as the design decisions are made. The later in a project designs are changed, the greater is the cost to pursue them. Figure 1. depicts a model of how the cost of design changes are affected during the lifetime of a project, and at which stage VE therefore would be most beneficial.

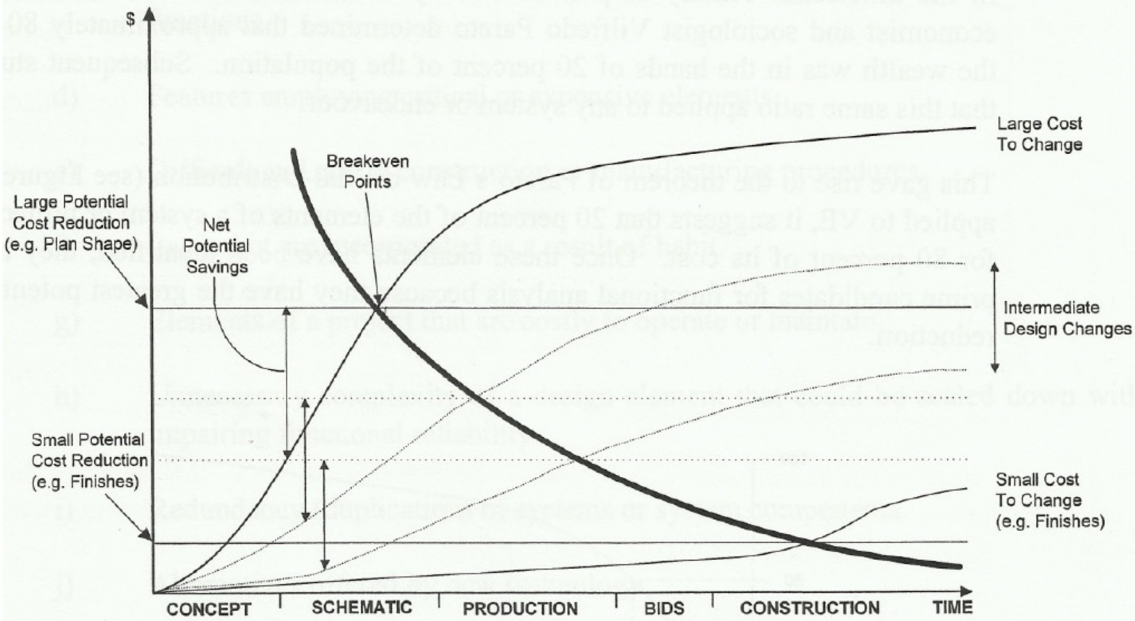

Figure 1. Potential savings from VE applications. (Atabay & Galipogullari, 2013).

Applying VE in an early stage of a project might be problematic, since the functions and alternatives for the given structure have to be well defined, in order to perform a trustworthy VE-analysis, and thus, the precise definition can be lacking in the early stages of a project. In VE, the alternatives analyzed are assumed to produce the same level of functional performance. In the early phases of a project there are interest groups involved, which could have a widely different understanding of the nature of different objectives. (Green, 1994). According to Green (1994), the term "hard thinking system" may be applied to functions and their solutions, that can be defined in a very exact manner, such as with technical characteristics. In a corresponding manner, Green names functions that cannot be defined in an exact manner for "soft thinking systems" such as political and aesthetic values, which are primary present in the early stages of construction projects.

All building projects are unique and especially the architectural design can vary a lot between projects, and is in addition an area where soft thinking is more present than in pure structural design. However, there are always technical functions that are demanded by law and which characteristics can be defined rather clearly. In this study, these characteristics will be mapped for foundations and base floor structures. Different functional alternatives will then be examined as a part of a VE-analysis. Moreover, these results can be utilized as an input in the early stages of a construction project, to provide guidance when soft system thinking is present.

2.4 The job plan

As a part of the VE process, a job plan is defined. The job plan has different stages and the number of stages can vary. Mandelbaum and Reed (2006) present eight different phases:

- Orientation phase
- Information phase
- Function analysis phase
- Creative phase
- Evaluation phase
- Development phase
- Presentation phase
- Implementation phase

During the orientation phase preparations for the value analysis are executed. This implies defining the problem that should be analyzed and collecting data. The value analysis is mainly done in the information phase and is finalized in the development phase. Thereafter, in the presentation phase, the results from the value study are presented as recommendations and input for decisions makers. The implementation phase is the last phase and is takes place after the value study, when the results from the study are put in to action. (Mandelbaum & Reed, 2006). This research project does not include an implementation phase, and thus, the results should rather be regarded as recommendations and input for building projects. Furthermore, building project that benefit from recommendations in this study can be considered the implementation phase.

2.4.1 The orientation and information phase

In the orientation phase, the problem or problems that will be addressed in the value study should be addressed. In the orientation phase the issues and the benefits for solving these issues are defined, the scope and objective of the study are established, as well as the measurable evaluation parameters, key cost drivers are defined, and the data is collected. (Mandelbaum & Reed, 2006).

In the present project, the orientation phase can be viewed as the definition of the objective of the study and its scope. In more detailed form, this implies that the issue in the present study is to find the most cost-effective foundation and base floor solution for small houses with a wooden superstructure and that the building lot has good load bearing capabilities or is bedrock.

The benefit of this study is therefore to save money when constructing a small house, whilst the functions of the building are not reduced. The measurable parameters are the cost of the structures, yet only the cost that is specific for the alternative will be analyzed, and therefore costs that are general for all different alternatives will be left out. Except for the cost of the structures, key cost drivers are excavation and mining costs.

In the information phase, the steps taken in the orientation phase are finalized and the last modifications to the scope and objective are done (Mandelbaum & Reed, 2006). In this study, no distinction between the orientation and information phase has to be done. Although the scope can be refined, as the functions of the alternatives analyzed should be those stipulated as mandatory by law or by the building code.

2.4.2 The functional analysis phase

In the functions analysis phase the functions of the structure are determined. In VE, the functions have to be defined in the form of a verb and a noun, respectively. The verb should answer the question of what the function does, and the noun should answer why it does it. (Mandelbaum & Reed, 2006). The functions in this study are gathered from mandatory functions for structures determined by law. These functions will probably (will be determined in regulation chapter) be the areas strength and stability, ground frost, thermal insulation, radon gas, and moisture protection. In concordance with the VE, these areas can be presented as functions with a verb and a noun as follows: withstand loads, avoids ground frost, fulfill heat transfer coefficients, mitigate radon gas seepage, and avoid moisture damages.

Secondly, the functions should be classified as either basic or secondary functions. The basic functions need to answer the question “what must it do?” and the secondary functions the question “what else does it do?”. (Mandelbaum & Reed, 2006). As the functions in this study is determined by law and therefore are mandatory to fulfill, it is not possible to define them as either basic or secondary, and thus, all should be regarded as basic function.

Thirdly, functions relationships have to be developed. This can be done by making a Function Analysis System Technique (FAST), whereby using this technique a FAST-diagram is developed that visualizes the function relationships in a very efficient manner. (Mandelbaum & Reed, 2006). A FAST diagram is illustrated in Figure 2.

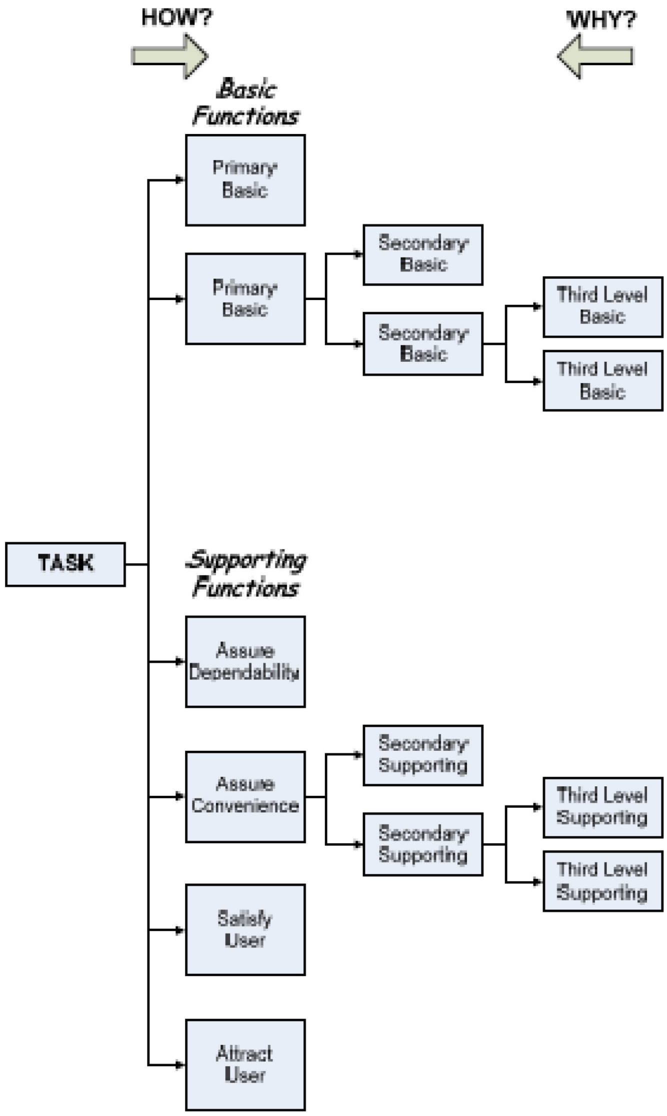

Figure 2. FAST-diagram. (Mandelbaum & Reed, 2006).

The FAST-diagram is structured with the main task to the left and the basic and supportive functions to the right of it. Beginning with the primary basic functions to the left, these can be split into various secondary basic functions when moving to the right. All the secondary basic functions that are connected to one primary basic function have to be fulfilled in order to complete the basic function. The logic behind this is the following: the more you move to the right in the diagram, the more detailed will the functions be on HOW the primary functions will be fulfilled. Vice versa, when moving to the left in the diagram, the answer on WHY a secondary function is needed to fulfill the primary function is presented. (Mandelbaum & Reed, 2006).

In this study, the task can be defined as the following: construct a foundation and a base floor to a small house with a superstructure made out of wood, on a building lot with good load bearing capabilities or bedrock, at the lowest cost to the customer but with structural alternatives that still can be approved by the authorities. The primary basic functions are then, as mentioned before: to withstand loads, avoid ground frost, fulfill heat transfer coefficients, mitigate radon gas seepage, and avoid moisture damages.

The primary function of withstanding load can be broken down into the following secondary functions: transfer load, withstand base floor load, withstand load from superstructure, control base floor span widths, and size the footing. Further, the function to avoid ground frost damages could be broken down into: keep load carrying soil from freezing and avoid pipes from freezing. The basic primary function to fulfill heat transfer coefficients could be broken down into: stop air movements and decrease heat conduction. The primary function addressing radon mitigation can be broken down into the following secondary functions: ventilate base floor and construct airtight base floor. The last primary function concerning avoiding moisture damages is broken down into the following functions: master diffusion, break capillary flow, lead water, and master humidity. The meaning of the different functions will be explained further in the chapters devoted to each primary function.

Fourthly, the cost of performing each function has to be determined. In this study, cost data is not directly linked to function but to structural solutions that fulfill the functions. The technical solutions to functions will therefore first be determined and thereafter the cost will be linked to these solutions. Thereby, will the cost data used in this study, be determined to the functions not until the solutions have been determined in the creative phase.

The most important thing is for making a reliable cost estimation, is to use reliable cost data. (Mandelbaum & Reed, 2006). In the present study, the cost data will be adopted from the book Rakennusosien kustannukset 2016 (in english: Cost of building parts 2016). This book is published every year, and thus the cost data is updated according to the year when it is published. The book follows the Talo 2000- nomenclature and its presented structural solutions are up to date with the Finnish national building code regulations and recommendations, as well as with RT-index instructions (ROK, 2016). All costs in the present study, except the cost of the radon ventilation system used in slab on grade base floors, have been found in this book. Exceptionally, the radon ventilation system costs will be received from an interview with a plumbing contractor, as this area belongs to their service branch. All costs presented in this study, are costs without value-added tax (VAT), as it is general for costs, thus not affecting the cost comparisons.

In order to make a reliable comparative cost analysis, cost data origin must be the same in time and place. Thus, the data has to be captured from the same period of time, so that fluctuations in the general construction cost or inflation does not impact the results when comparing different alternatives. Otherwise, the cost data has to be index adjusted, in order to assure a reliable comparison of the data. In addition, the place has to be the same because construction cost can vary between geographical areas and if this not taken into account, the reliability of the cost comparison can suffer tremendously. In this study, the time will be set to year 2016 and the geographical area will be set as area number 3, which concerns areas with low construction cost (ROK, 2016). The choice of area number 3 is solely for practical reasons, since the index value in the data is given as 1,00 for this area (ROK, 2016) and therefore no index adjustments are needed for the data.

The final step in the functional analysis phase is to determine the best opportunities for improvement. This is done by checking which areas that should be prioritized, whereas it is often not wise to investigate all possible functions, if they for example compass only an insignificant amount of the cost. Therefore, functions that carry a bigger portion of the total cost are usually prioritized, since they have a higher probability to affect the cost performance. (Mandelbaum & Reed, 2006).

In this study, the functions will not be prioritized at this early stage of the process. The best opportunities for improvements will be assessed at the end of the study, when all cost data is on the table. Nevertheless, some aspects that could act as opportunities to reduce cost will be presented during the creative phase.

2.4.3 The creative phase

In the creative phase, a large number of ideas for different solutions to perform each function are created. The creative phase can be conducted using an analytical or creative approach. The difference between these two approaches is that the analytical approach represents the idea that there will only be one solution to the function that will work, compared to the creative approach where the function can be fulfilled using many solutions. (Mandelbaum & Reed, 2006).

The creative approach is, thus, better suited for the analysis conducted in this study, since there are many different solutions for constructing a functional foundation and base floor. The next step using the creative approach, is to search for the optimum solution among solutions at hand (Mandelbaum & Reed, 2006). This step will be conducted in the chapters regarding each function, whereby different solutions will be presented, yet the optimum to cost will be adopted.

In order to perform the creative phase successfully, creative inhibitors should be avoided. Mandelbaum and Reed (2006) list common creativity blocks such as habitual, perceptual, cultural, and emotional blocks. Habitual blocks comprise for example that the team members have problems seeing possibilities in alternative solutions as they have a strong bond to habitual solutions. To avoid creative blocks, demands are set on the team members to be objective to alternative solutions and to avoid bad attitudes and prejudices against new ideas. Different attitudes to be avoided in this phase are listed by Mandelbaum and Reed (2006) and are called “Good Idea Killers”.

Next, ground rules for the idea creation are established. Mandelbaum and Reed (2006) have listed seven ground rules for idea creation, of which only the most important rules for this study will be cited. One of the rules stipulates that the ideas should not be created and judged at the same time, as the judgment should be left to the evaluation phase. The following statement could constitute an example for the present study: A pillar foundation saves material in the foundation, but the extra thermal insulation in the base floor makes it unfeasible. According to another rule, there should be a diversity and variety of ideas, and see if different ideas could be explored and combined. Finally, another central rule stipulates that the ideas are not allowed to be ridiculed or put away in the creative phase. (Mandelbaum & Reed, 2006).

Finally, the ideas are generated. Methods for generating ideas are for example brainstorming, the Gordon technique, Checklist, or Theory of Inventive Problem Solving (Mandelbaum and Reed, 2006). In the present study, the creative phase is not directed towards finding completely new ideas, but to determine which solutions are accepted in the literature, whereby the author will use and mix the different alternatives, in order to generate the optimum solution in the group gathered.

2.4.4 The evaluation phase

In the evaluation phase, the generated ideas are processed in order to select the best ideas for further development. Less potential ideas, due to lack of feasibility or function performance, will be eliminated here (Mandelbaum & Reed, 2006). In this study, all the solutions that are examined fulfill the functions, and therefore ideas will be eliminated due to cost solely.

The ideas should be grouped into different subject-related categories (Mandelbaum & Reed, 2006). In the present study, these categories are foundation structures and base floor structures. These two parts combined form one functional solution. The study will be conducted so that the most cost effective solutions are examined in each category. After that, the combination of alternatives derived from the two different categories will be compared in the development phase.

It can be assumed, that the most cost effective foundation and base floor combination will be the combination of the two most cost effective solutions in each category. Nevertheless, it might be that these solutions are not compatible for structural reasons. Thus, the structural concordance of alternatives derived from the categories must be addressed when combining them.

Then, the advantages and disadvantages of each idea are listed. These pros and cons could be based on cost, savings potential, time to implement etc. (Mandelbaum & Reed, 2006). In this study, the cost factor represents the only advantage or disadvantage. The ideas are ranked according to the factors applied to them. The ranking applied in this study will be rather straightforward, since it is merely based on cost values.

Finally, the best ideas will be chosen for further development, via the ranking executed before. The ideas not chosen are excluded at this point, in case it is concluded that they are not the optimum one. The cost for base floors will be defined in €/m2 and the cost for foundations in €/m, at the end of the evaluation phase.

2.4.5 The development phase

After the development phase, the best alternatives are ready to be presented as recommendations to decision makers. In this phase, a more detailed technical analysis can be developed according to the alternatives. The activities executed in this phase comprise a life-cost-analysis, the determination of the most beneficial alternatives, and the development of implementations plans. (Mandelbaum & Reed, 2006)

Because the focus of this study is on designs in a more conceptual, rather than detailed stage, no more technical analyses need to be done. Neither must a life-cycle-cost analysis be made, because the analyzed structures do not include any significant maintenance or operational cost. The cost analysis made is on the investment cost of the structures solely. The investment cost will be determined by pairing foundation alternatives with suitable base floor alternatives, and by applying the variables x and y to build a formula that gives a comparable cost value. The variable x will be the length, and y the depth of a rectangular building. By applying these formulas, it will be analyzed which combinations are the most cost efficient from an investment cost perspective, and if the building measurements affect the cost efficiency.

2.4.6 The presentation phase

In the presentation phase, the findings from the value study are presented to the decision makers. It is then up to the decision makers to decide if they want to apply the results further to the implementation phase (Mandelbaum & Reed, 2006). In this study, the concluding chapter can be regarded as the presentation phase, as the findings of the study are presented there.

2.5 Summary of VE analysis in this study

In this study, the introduction in combination with the chapter on value engineering represent the orientation and information phase. The function analysis phase is initiated in the regulation chapter, as the basic primary functions are defined there. The function analysis phase is then finalized in the chapters devoted to each primary function and the secondary basic functions will be determined there.

The creative phase mostly occurs in the chapter about load bearing structures, where the main structural alternatives are defined. Nevertheless, the creative phase spills over to the function chapters as solutions to the primary functions and secondary functions are presented there. The evaluation phase starts with the function chapters, with evaluating functional cost that is only dependent on a single function. For example, two thermal insulation materials with the same characteristics but different cost will be evaluated in the thermal insulation chapter and the less cost-efficient will be cut out immediately in the chapter.

The evaluation phase will continue in a specific chapter, where further evaluations will be executed. These evaluations will consider costs that are bond to more than one function, for example, the combined cost of a load bearing structure and thermal insulation in a base floor. The evaluation chapter will end with having a set of complete alternatives for foundations and base floor structures that will be developed in the development phase.

In the development phase, foundation and base floor structures will be combined in a suitable way in order to make them work together as a unity. Then formulas will be developed, so that the comparable cost of each combination can be accounted for with the variables x and y, length and width of a building respectively. After that, the results will be analyzed and discussed. The costs calculated in this project, are the only costs needed to compare the different alternatives, and thus, costs that are general for all alternatives have been excluded. Therefore, the values from the formulas cannot be used to calculate bids or total construction cost.

Finally, the results and recommendations are presented in the conclusion, which is regarded the presentation phase in this value analysis process.

3 Regulations affecting foundations and base floor structures

Laws and regulations determine construction and land use in Finland. Therefore, the law imposes a central framework, within which all of the construction planning and cost optimization takes place. Hence, this section will provide an overview of laws and regulations that apply for design and construction of foundations and base floor structures, and the mandatory characteristics that have to be fulfilled. Instructions published in connection to the regulations will be examined in the following section as well. Laws, regulations and instructions differ in the sense that laws and regulations are mandatory to follow, whilst instructions are merely recommendations.

Supreme in the legal hierarchy is the law named *Land use and building act*. Subordinated to the law are the different decrees published by The Finnish Ministry of Environment. They provide more detailed regulations than the law of *Land use and building act* itself, in order to complete the law and assist the interpretation of the law. The local building code and zoning regulations pose the lowest degree of the legal hierarchy (Ekroos, 2005).

3.1 Land use and building act and decree

The current *Land use and building act* (5.2.1999/132) and *Land use and building decree* (10.9.1999/895) became effective January 1st 2000. The act is mostly written in a very general way, to be completed by decrees and instructions. Nevertheless, the minimum physical requirements for construction are stipulated in paragraph 117 (Ekroos, 2005).

Paragraph 117a states that the structures of a building have to be solid and stabile, applicable to the characteristics of the building site and last for the projected age of the building. Furthermore, the building material used has to be applicable to its intended applications. Moreover, the building structures have to be designed in a way so that applied stress during construction and usage will neither cause collapses, nor strength and stability harming deformations. (5.2.1999/132, 2000). These requirements are met through appropriate structural- and geotechnical design, in accordance with the building code or Eurocode applying for the specific situation.

Further, paragraph 117c declares that a building has to be designed and build to be safe and healthy, with respect to indoor-air quality, moisture and water management. The building should not cause health risks by indoor-air impurities, radiation, water or ground deterioration, smoke, insufficient waste water and waste management, nor moisture in building parts and structures. (5.2.1999/132, 2000). In this paragraph, the significant aspects for foundations concern humidity and water control. For base floors radiation is a main concern, together with humidity control, because of the appearance of radon gas on many building lots.

Paragraph 117g proclaims that a building should be designed and build using energy and natural resources sparingly. It also mentions that Ministry of Environment through decree can give regulations that are more exact when it comes to minimum demands for energy efficiency of buildings and buildings parts. (5.2.1999/132, 2000). In this paragraph the most concrete thing affecting foundations and base floors, is the energy efficiency and with that thermal insulation and airtightness of the buildings envelope. In this study, the cost differences are examined, and thus, the wise usage of natural resources is not further investigated here.

The *Land use and building decree* does not include anything in direct coherence to foundation and base floor structures, except for paragraph 55 regarding ecological aspects in construction. The paragraph states that a building has to be for its ecological characteristics durable for its intended use. In the design state, if required, the environmental impact of building materials and products shall be clarified. Particular respect should be given to the ability to retrofit and repair building parts and technical building systems. (10.9.1999/895, 2000). Cost is the main focus in this study and the ecological characteristics will not be investigated here, but the result of this study might give input to this area. Further, if foundations and base floor structures are designed for a life span of 100 years, the ability to repair and retrofit them should be of a subordinated importance.

3.2 Decrees by the Ministry of Environment and the National Building Code

3.2.1 Decrees by the Finnish Ministry of Environment.

Decree 465/2014 is applied for the design and construction of both permanent and temporary building foundations. In the second paragraph, the regulations from the building law concerning strength, stability and deformations are repeated, nevertheless specifically referring to foundations in this case. The third paragraph concludes that the essential technical requirements of a building are fulfilled, if foundations and ground structures are designed and build according to the Eurocodes and their corresponding national annex. (465/2014, 2014).

According to the fourth paragraph, the circumstance of the building site and the immediate surroundings, including buildings and foundations, shall be accounted for when designing the foundation. The foundations and ground structures shall be designed in a way that prevents harmful effects from ground moisture entering the structures, as well as harm and damages caused by ground frost. In addition, the risk of dangerous radon gas on the building site should be accounted for. (465/2014, 2014).

In paragraph six it is pointed out that ground conditions of the building site has to be examined through a ground examination. Paragraphs 7-11 comprise mandatory plans, drawings, implementation documents, and their needed contents enumerated. (465/2014, 2014). For small house foundations, the necessary documents and their extent of detail is determined by the construction authorities and can vary with the characteristics of a specific project. Usually, structural and construction drawings, soil-testing report, ground frost insulation plan, and drainage and rainwater system plans are mandatory documents. In Decree 12.3.2015/216, the required characteristics included in a ground and foundation condition examination are specified, which, in turn, can vary between projects. (12.3.2015/216, 2015).

By decree 477/2014, valid from September 1st 2014, the load-bearing and bracing structures of a building have to be designed according to Eurocodes and their corresponding national annexes. This implies that foundations and base floors should be designed in accordance with the corresponding Eurocode, depending on which material (masonry, concrete, steel, and wood) is used for the structure.

3.2.2 The Finnish National building code

The *Finnish National Building Code* is published by the Finnish Ministry of Environment. In the legal hierarchy, the *National Building Code* is considered a decree (Ekroos, 2005). During the last years, many parts of the *National Building Code* have been replaced by decrees enforcing the use of Eurocodes, yet there are still parts that are active and thus, have to be mentioned here.

Part D1 (2007) handles the regulations of the water- and sewer installations for real estate. It stipulates that the water and sewer installations have to be constructed in a way so they cannot freeze. Water pipes and sewers have to be insulated in a sufficient way or heated if they are in a cold space or above the ground frost level. This can apply for a small house in case the incoming water pipe or outgoing sewer is installed above the ground frost level, or in case it is installed above ground in a crawl space. Furthermore, D1 (2007) demands that the rainwater system has to be built in a well working way, as well as that the rainwater cannot be led in the same pipe as the foundations drainage water. The rain and drainage water is then led to an open ditch, a public rainwater sewer or have to be absorbed in the ground. If the rain and drainage water have to be absorbed into the ground, a rock pocket has to be built, which has to be accounted for in the cost-calculations (D1, 2007). Part D2 (2012), handling buildings indoor-air and air-conditioning, gives the maximum allowed level of radon gas in a building. Further, it demands that the air-pressures and structural sealing capabilities are designed and constructed in order to reduce the seepage of radon gas into the building (D2, 2012).

The Finnish National Building Code part C2 (1998) consists of regulations and instructions about preventing harm and damages originating from moisture. C2 (1998), states that the surface and ground water characteristics of a building site, have to be taken into account, deciding the elevation of a building. In addition, all humus and organic material have to be eliminated beneath the building and from backfills around the building. Further, C2 (1998) states that harmful capillary flow to and through structures is to be blocked by drainage layers, water and moisture insulation.

According to C2 (1998), rain and melt water has to be led away from a building. The ground under and around the building shall be drained to stop the capillary water movement and keep the ground water level on an acceptable level. Further, it states that the level of a base floor on ground should be at least 0.3 meters above the surrounding ground level. A base floor with crawlspace shall be designed and build so that ventilation is sufficient and water cannot cumulate inside the crawlspace. The connections between walls and foundations, or ground-based floors, shall prevent moisture transfer between the building parts (C2, 1998).

Section D3 (2012) regulates energy efficiency of buildings and thereby the characteristics of thermal insulation and airtightness of the buildings envelope. In this section, the minimum level of heat conductivity allowed in different building parts, base floors included, is specified. It is also stipulated that the thermal insulation of the base floor has to be designed together with the ground frost insulation, in order to make a functional whole. Moreover, D3 (2012) stipulate the level of the airtightness of the buildings envelope of which the base floor structure is a part.

3.3 Local building codes and zoning regulations

All cities and counties are obligated to have their own local building code, which could differ based on the area of the city or county as well (Ekroos, 2005). The local building code can regulate methods of construction, building placement, plantations, water-management etc. However, town plans and the national building override the local building code in case these regulations collide (Ekroos, 2005). In this study, no evidence has been found that local building codes enforce regulations on foundations and base-floor structures, and therefore local building codes will not be included in the study.

Zoning regulations for specific areas or town plans can affect the foundations and base floor structures, if they regulate the construction method or material that has to be used in buildings in a specific area. There are for example zoning regulations areas that enforce use of ecological material, and state that the load bearing structures have to be made out of wood. In these cases in particular, the base floor structure could be affected by zoning regulations. In this study, zoning regulations will not affect the structures that are examined, but the research results could be a valuable input for zoning executives.

3.4 Summary

Summarizing the regulations, there are five main functions that have to be taken into account when designing and constructing functional and legal foundations, as well as base floor structures. These are the following functions:

1. Structural strength and stability
2. Ground frost
3. Water- management and moisture
4. Radon gas
5. Energy efficiency

These are equivalent to Hemgrens (1998) functions enumerated in the introduction. In the following chapters, these areas will be further examined and evaluated.

4 Load bearing structures

The function of a load bearing structure is to carry loads and transfer loads (Millais, 1997). The function of a foundation and base floor is to carry the loads imposed on them and transfer them to the ground. The loads imposed on a base floor are the self-weight of the structure and useful load applied by usage of the building, in this case people living there. The loads are then transferred from the base floor directly to the ground in a concrete floor on ground (CFG) base floor or to the foundation in a base floor supported by the foundation. The loads on a foundation are, besides the loads applied by the base floor, self-weight, the self-weight of the superstructure and the snow, wind and useful loads applied on the superstructure. The loads are then transferred through either pillars or a foundation wall to a footing that transfers the load to the ground.

4.1 Foundation methods for small houses

In order to choose a foundation method, the ground condition of the building lot, the terrain shape, the leveling of the courtyard area, potential basement and the superstructure have to be taken into account (RT 81-10486, 1992). In this study, the following assumptions are made: the ground condition is firm soil or bedrock, the terrain shape is rather leveled, the courtyard do not affect the foundation, no basement is planned, and the superstructure is made of wood. A small house foundation is usually made out of steel reinforced concrete, either cast in place or by elements, built of light weight concrete blocks, and concrete pillars. Building on firm soil, foundations and base floors can be chosen rather freely, whereas on bedrock there is reason to avoid mining as much as possible, due to the mining costs (RT 81-10486, 1992).

The different foundation methods comprise wall footing with a foundation wall, pillars with pillar footing, and a stiffened raft-slab foundation. The base floor can be either self-supported or supported by the ground. (RT 81-10486, 1992). The minimum foundation depth is 500mm (RT 81-10854, 2005). The level of the upper side of the CFG base floor is set to be at least 300mm above the outside ground level. The height inside a crawl space should be at least 800mm. (C2, 1998).

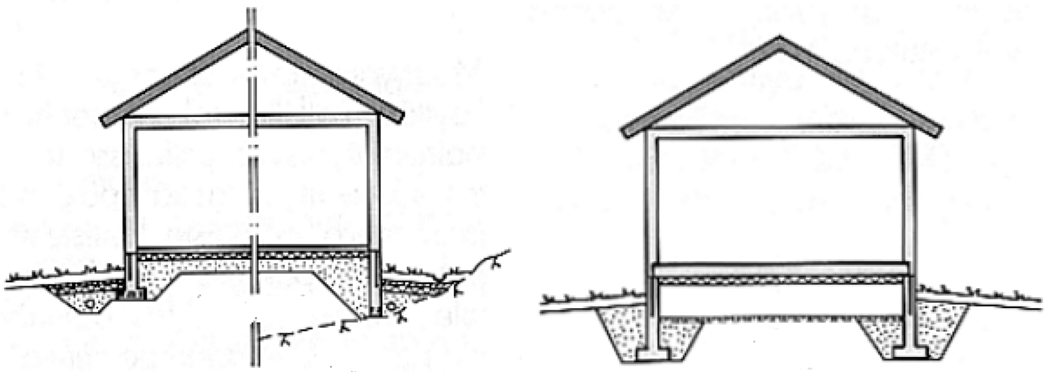

Figure 3. A foundation wall with CFG (left) and foundation wall with self-supported base floor (right) (RT 81-10486, 1992).

The ventilation holes in the foundation wall should be placed at least 150mm from the ground and be at least the size of $150cm^2$ (C2, 1998). Assuming that the holes are 10x15cm, the distance from the underside of base floor structure and the outside ground level is required to be at least 300mm for them to fit.

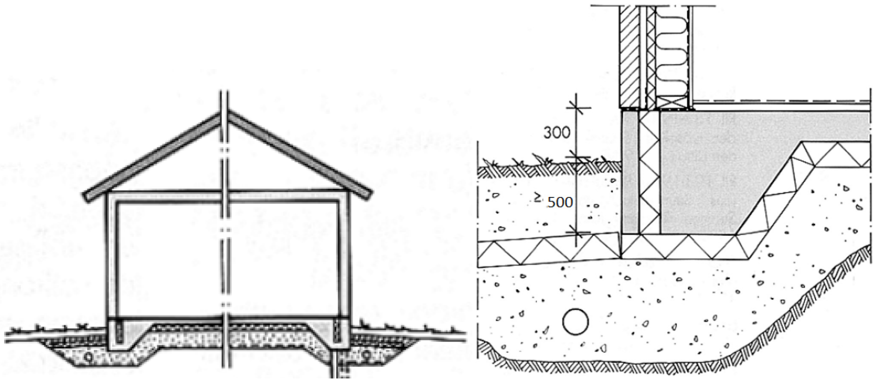

Figure 4 and 5. Stiffened raft-slab foundation (left), Minimum level above the ground and minimum foundation depth (right) (RT 81-10486, 1992).

If the foundation is supported directly by bedrock, usually no separate footing is needed as the pillar can be directly attached to the rock (RT 81-10486, 1992). In general, the bedrock quality in Finland is very good, and therefore concrete structures can be directly built on bedrock (Jääskeläinen, 2009.). The foundation and base floor alternatives are many, and thus by rationalization the most common have been selected for the analysis.

4.1.1 Pillar foundation

Pillar foundation can be used in small houses where the loads on the foundations are not very high. The pillars can be made out of cast in place concrete, or lightweight concrete (LWC) pillar blocks, that are filled with concrete. The LWC pillars will be the only pillar foundation examined in this study, as it is the only pillar alternative where cost data available. The pillars can be assumed to be distributed at a 3000mm distance from each other supporting the outside wall of the building (ROK, 2016). An extra row of pillars underneath the house, located at center of the smaller side of the building must be built as well, in order to support the base floor. The pillars are supported by a pillar footing or directly by the bedrock. The pillar footing will be assumed to be 600x600x200mm (ROK, 2016).

Since pillars alone cannot support a concrete based base floor, the base floor has to be made out of wood. To support the distance between the pillars, an additional wooden beam is installed on and between the pillars, in order to transfer the load from the superstructure and the base floor to the pillars. The beam is built by putting two base floor beams together (RT 81-10854, 2005). This has to be accounted for in the cost-analysis.

4.1.2 Foundation wall foundation

Foundation wall foundations consist of a continuous foundation wall underneath the outside wall which is supported by a continuous wall footing. With a self-supported base floor structure, an extra foundation wall might be needed at the center of the building, depending on if required by the span width. The footing is usually made of concrete and cast in place, except in those cases where it is integrated in the foundation wall element. The footing can be both continuous or with a distribution of 3000mm in those cases, the foundation wall acts as a beam (ROK, 2016). The continues footings are assumed to be 600x200mm and the beam footings 600x600x400mm (ROK, 2016).

The foundation wall can be made out of elements or built in place. There are two kinds of elements: a hollow-core concrete beam, and an EPS-form element that is cast in place. In the latter, the footing is integrated in the element. When it comes to cost, the

EPS-concrete beam is more effective and will thus be the only element analyzed. (ROK, 2016). The element wall can be used both in self-supported or with CFG base floors. When comparing elements to the built-in-place solutions, the element has a specific measurement and the foundation depth cannot be adjusted in the same way as in the built-in-place solutions.

The built in place foundation walls can be made of LWC-blocks or cast-in-place concrete. The LWC wall must be 290mm thick and covered with a 50mm EPS layer on the inside (RT 81-10854, 2005). The LWC wall is smoothed with plaster to make it airtight and protected from water (RT 81-11099). The LWC foundation can be used both in self-supported and with CFG base floors.

A cast in place wall that is 300mm thick and have an 80mm layer of EPS in the middle, works as a foundation wall both to support base floor slab and with a CFG. However, when directly compared to the LWC wall, the concrete wall is 33% more expensive than the LWC alternative. Therefore, the LWC wall is the only build in place foundation wall that will be examined.

4.1.3 Stiffened raft-slab foundation

A stiffened raft-slab foundation consists of a concrete slab with thickened edges under the outside wall. The slab is acting both as a base floor slab and a foundation, and has to be casted in the same time. In the center of the building the structure is the same as in a normal CFG base floor. The foundation depth on perimeter walls cannot be adjusted for structural reasons, and is then set to 500mm as the minimum demand (See Figure 5.). (RT 81-10854, 2005).

4.1.4 Concrete floor on ground base floor

A CFG base floor comprises an 80mm reinforced concrete slab on the top and thermal insulation and a capillarity-breaking layer underneath. The characteristics of thermal insulation and capillarity-breaking layer are examined in their respective chapters.

4.1.5 Wooden base floor

A wooden base floor structure consists of a 300mm high wood frame with thermal insulation within. The wood frame is higher in a pillar foundation, if required by the amount of thermal insulation. The foundation wall or the beam that transfers the loads to the pillars supports the wooden base floor. On the underside, it is covered with wind breaking boards, if demanded by the thermal insulation material. On the top of the frame a wooden floor or a veneer board could be placed, on which a concrete floor slab is cast. In this analysis, the veneer and floor slab will be chosen, in order to make it more comparable to the other alternatives. The concrete slab on a wooden frame need only to be 60mm thick. (ROK, 2016). The span width of a 300mm high wood frame could be as much as 5,5m (www.metsawood.com, 2017) and therefore it is assumed that extra support is needed in the middle of the building. The extra support is executed in the same way as in the pillar foundation.

4.1.6 Hollow-core-slab base floor

A hollow-core-slab (HCS) is a precast and prestressed concrete slab. It is supported by the foundation wall and has thermal insulation either on the top or underneath. The thicknesses can vary, yet a 200mm thick slab have maximum span width of 11,0m (http://www.elementtisuunnittelu.fi, 2017). Therefore, it is assumed that no extra support will be needed in the center of the building, and thus it is supported solely by the foundation walls.

If the thermal insulation is on the underside, the floor slab only needs to be 40mm thick. If the thermal insulation is above the HCS on the other hand, the floor slab has to be 80mm thick. According to the cost data, the solution with insulation on the top is ca. 8% more costly. (ROK, 2016). Therefore, merely the alternative insulated beneath the slab will be included in the analysis.

4.2 Foundation and base floor combinations

For the final cost analysis, the most cost effective solution of each structure cannot be chosen at once. First, it has to be examined and assured that the foundation and base floor solution can be combined to a functional unity. The compatible combinations are presented in Table 1 below. The crosscheck in the boxes tells that the combination is executable.

Table 1. Compatible foundation and base floor combinations (RT 81-10854, 2005)

	Base floor alternative		
Foundation alternative	Wood frame	HCS	CFG
Pillar	x		
Foundation wall	x	x	x
Raft-slab			x
HCS=Hollow-core-slab CFG=Concrete floor on ground			

5 Radon gas in mitigation in small houses

5.1 Radon gas and buildings

Radon is a radioactive noble gas that is formed in the ground and bedrock when uranium is degraded radioactively (Jääskeläinen, 2009). The gas is invisible and odorless and can only be observed by special measurement equipment (STUK, 2014). The unit for radioactivity is Becquerel (Bq) and the level of radon gas in indoor-air is given in Bq per cubic meter air (Bq/m³) (STUK, 2014). Radon gas in the indoor-air accounts for ca. 300 cases of lung cancer each year in Finland (Arvela et al, 2009). Radon gas is entering small houses by air seepage from the ground under the building through leaks in the base floor and foundation structures. Therefore, the mitigation of radon seepage is a basic function of the foundation and base floor structure that should be accounted for in this study.

Radon gas is present in most parts of Finland (see Figure 6.). Therefore, the risk of presence should be taken into consideration in the design phase in all small house projects in the country (RT 81-11099, 2012). In order to avoid mitigation actions, a written statement have to be made to the authorities, on the reasons why mitigation actions can be undone (Arvela et al, 2009). Many municipalities where the presence of radon gas is widely established, the local building code can enforce that radon mitigation actions have to be taken (Arvela et al, 2009). The average maximum level of radon gas in residential buildings in Finland is set to 200 Bq/m³ (D2, 2012).

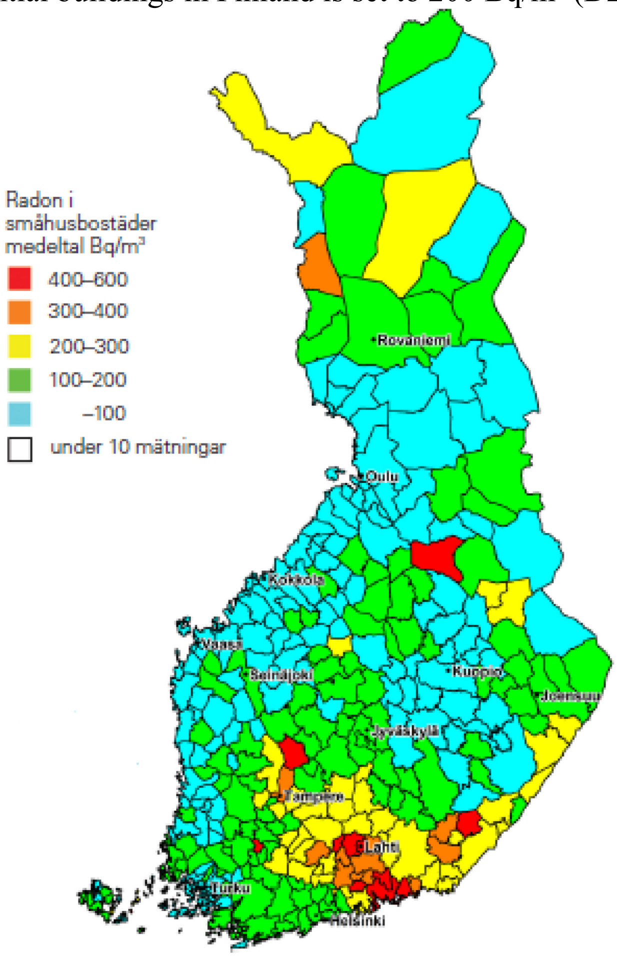

Figure 6. Average radon level (Bq/m³) in small house apartments (STUK, 2014)

Usually, the outside air is cooler than the indoor air, especially in the winter. This temperature difference creates a negative air pressure over the buildings envelope (Weltner, 2003). The air-conditioning system of a building is usually designed to keep a small negative air pressure indoors, compared to the outside, in order to prevent damages due to moisture (D2, 2012). The negative air pressure accumulated by temperature differences and ventilation systems create an airflow that drags radon-contaminated air in to the building through the base floor and foundation (Weltner, 2003). The contaminated air is seeping through joints and leading-in pipes and cables (Arvela et al, 2009). The usual leaking point is the joint between the base floor slab and the foundation wall (see Figure 7.).

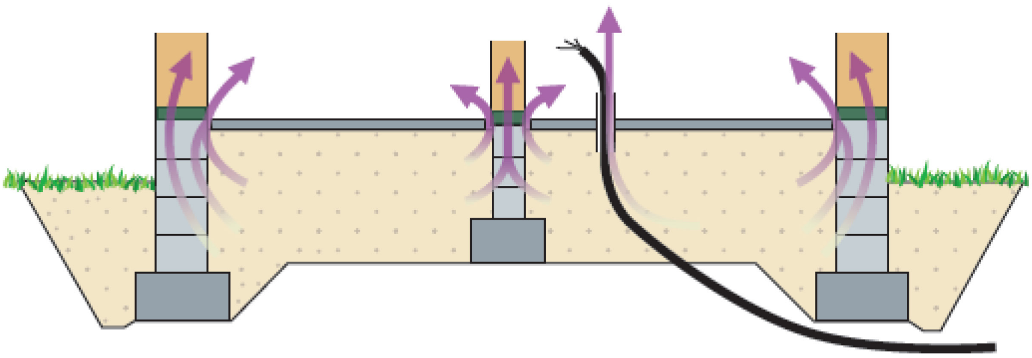

Figure 7. The most common seepage point for radon gas (Arvela et al, 2009).

5.2 Radon mitigation in different foundations

Different foundation and base floor alternatives affect the amount of radon-technical actions that have to be taken (RT 81-11099, 2012). This, in turn affects the total cost of the foundation and have to be accounted for in the comparative cost analysis. Important is, that the structural alternatives fulfill mandatory functional capabilities for radon gas mitigation and can be compared only on cost basis. The mitigation comprises sealing joints and installing air-ventilation pipes under the base floor.

5.2.1 Raft-slab and open-air ventilated crawlspace foundations

According to research, the radon concentration in buildings with raft-slab foundations and open-air ventilated crawl spaces are very low (Arvela et al, 2009). Raft-slab has a structure that is considered leak-proof, as the base floor slab and foundation are casted at the same time and, thus, are free of joints. In this case, no radon-technical actions have to be taken, except from sealing in-leading pipes and cables, in order to prevent seepage. (STUK, 2016). Anyway, the floor slab has to be at least 80mm thick (RT 81-11099, 2012).

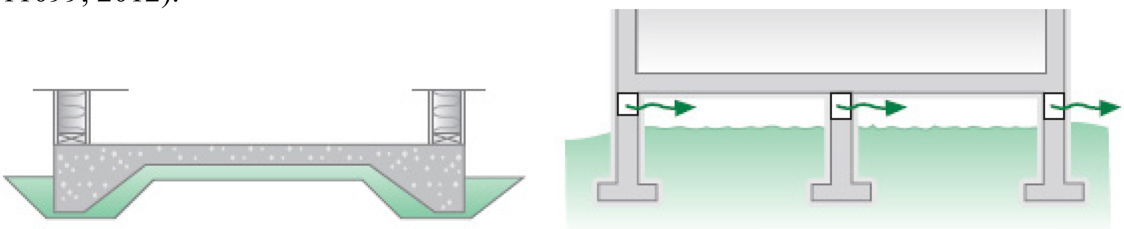

Figure 8. Slab-on-grade to the left and open-air ventilated base floor foundation to the right (Weltner, 2003).

From a radon technical point of view, the open-air ventilated crawl space comprises a safe structure, because radon-contaminated air is ventilated away before it can penetrate the base floor. Nevertheless, the base floor has to be airtight and possible joint, leading-in pipes and cables have to be sealed (RT 81-11099, 2012). Thus, the radon-mitigation actions do not cumulate any extra cost in these structural alternatives, as these sealing measures are general for all different structural alternatives. The radon risk is avoided by the choice of structural method itself.

5.2.2 Foundation wall with separate cast concrete floor on ground

A foundation wall with a separate cast base floor inside the house is a very common structural alternative, thus having most problems with radon gas. In addition to the sealing of cables and pipes, the joint between the slab and foundation wall has to be sealed as well. When the slab shrinks due to drying, the joint is causing a 1-5 mm gap between the slab and the wall, where seepage can occur (Weltner, 2003) (See Figure 2.). However, base floor slab has to be at least 80mm thick as in the raft slab solution to be a sufficient radon barrier in itself (RT 81-11099, 2012).

An accepted solution to prevent the seepage through the joint gap, is installing a membrane that overlaps the gap. The membrane is usually bitumen based and is on wall side fixed between the foundation wall and the wooden superstructure. On the same time, the membrane acts as a capillarity-breaking layer between the foundation and the superstructure. On the slab side the membrane is installed before the casting of the slab and is situated between slab and thermal insulation in the floor (see Figure 9.). The same method is used for partition walls breaching the base floor slab (RT 81-11099, 2012). From a cost perspective, this implies an extra cost, compared to the previous structures without the gap. The bitumen membrane has to be wider than in the cases where it only works as capillarity breaking layer and this will be taken into account in the cost-analysis.

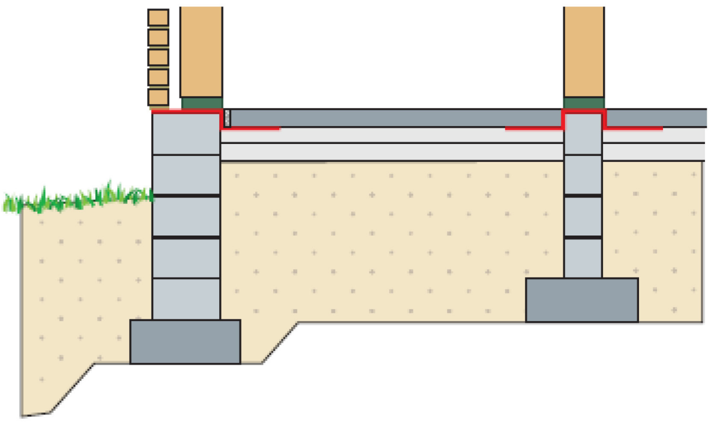

Figure 9. Membrane sealing the gaps between the foundation and the base floor slab (Arvela et al, 2009).

In addition to the membrane, an air-ventilation system is installed in the capillarity breaking macadam layer under the base floor. The function of the ventilation system is to ventilate the air in the macadam layer and to create a negative air-pressure beneath the base floor. In a small house, the system consists of a plastic drainage pipe that is installed in a circle ca. 1,5 m from the foundation wall and 20 cm under the thermal insulation. The drainage pipe is then connected to a sewer pipe leading up through and above the roof of the building, and is there covered with a rain hat (see Figure 10.). The sewer pipe, leading from the ground through the roof, has to be insulated in order to prevent the condensation of moist air indoors against the colder pipe. If the radon levels still are too high in the finalized building, an electrical fan is installed at the end of the pipe above the roof (RT 81-11099, 2012). This system has a considerable cost and will therefore be accounted for in the cost analysis. However, the fan alternative will be excluded in this study, since it can be considered the worst-case scenario.

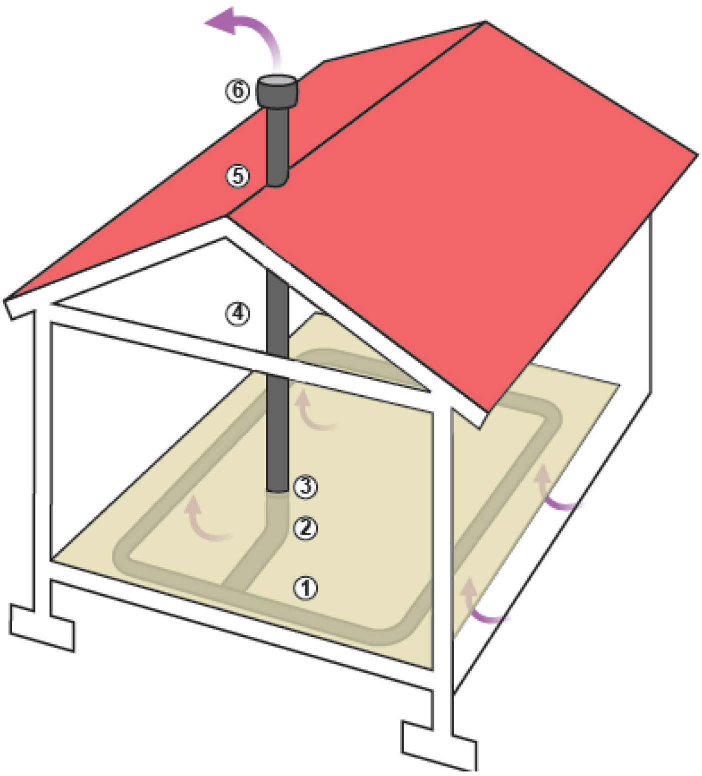

Figure 10. Air-ventilation system under the base floor (1=drainage pipe, 2=sewer pipe, 3=sealed through hole in the base floor, 4=insulated sewer pipe, 5=water tight sealing in the roof, 6=Rain hat or if necessary electrical fan) (Arvela et al, 2009).

The cost of the ventilation system comes from the installation and material cost. The cost of the drainage pipe can be accounted with the variables x and y, length and depth of the building respectively, when cost of the pipe is 6,26 €/m for both material and installation (ROK, 2016). The installation of the insulated sewer pipe, roof sealing and rain hat can vary a little bit with the height of the building. However, a trade-off assumption can be made, that it has to be 8 m tall in a small house. The cost of material for an insulated sewer pipe and its roof installations is 708,19 € without VAT. In addition, the installation takes ca. 8 hours and the cost of labor is 361,28 € (no VAT). (Lindström, 2017.) The total cost of for both material and labor for the 8 m pipe with roof installations is then 1069,47 € without VAT. The cost of the radon ventilation system (RVS) for a building can then be calculated with the Equation 2. below, where the variables x and y are the length and depth of a building respectively. In the equation, the length and width of the building are subtracted with 3 m (2*1,5 m), as the pipe is installed 1,5 m from the wall in both directions.

Equation 2. Total cost of RVS in a building

Cost of RVS (€) = 2*((x-3)+(y-3))*6,28+1069,47

By algebraic simplification, the equation can be written as following:

Cost of RVS (€) = 12,56x + 12,56y + 994,11

This cost will be added as a part of the total cost of a foundation with a separately cast concrete floor on ground, in the cost comparisons.

6 Moisture management

6.1 Moisture

Moisture is equivalent to water in all its states of matter, which is water vapor, liquid or ice (Nevander, 1994). According to Nevander (1994), foundations are probably the structure most affected by moisture damages in small houses. Moisture is causing a vast array of different damages to buildings, the most well-known being mold and putrefaction of building material. These damages can cause great health risk and are usually very expensive to repair. Thereby, the moisture-safe design is one of the most important technical features of a building. In this section, moisture in vapor and liquid form will be further examined. Ice, on the other hand, will be examined in the ground frost chapter.

6.2 Moisture sources

According to Nevander (1994), the main sources of moisture in buildings comprise rain and snowfall, air humidity, moisture from the construction phase, water in and on ground, and leakage (See Figure 11). Moisture stemming from the construction phase is a surplus of moisture, which will be eliminated once the building has dried enough and reached a moist equilibrium. Problems from this moisture sources may occur if the construction parts have not dried adequately before being covered. In any case, moisture from the construction phase does not add any cost to the base floor and foundation structures, as it reasonable to assume that the cost data in the literature demonstrates values for construction work performed correctly i.e. also dried adequately. Leakage damages do not affect the foundation or base floor investment cost, since they occur later during the usage of the building.

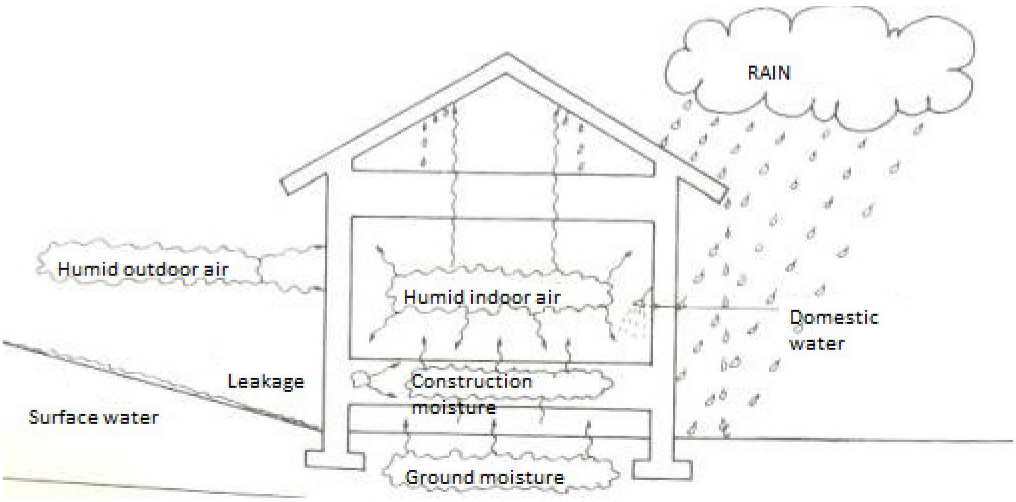

Figure 11. Moisture sources (Sisäilmayhdistys ry.,2008)

6.3 Moisture transfer

Moisture transfer can occur in various ways, in vapor as well as in liquid state. Vapor transfer can occur due to diffusion and convection. Moisture transfer due to diffusion occurs because gas molecules in a higher concentration move towards a lower concentration, until the concentrations are equal (Nevander, 1994). For example, the absolute humidity is usually higher indoors than outdoors, thereby creating a moisture transfer through diffusion over the envelope of the building (Nevander, 1994).

Transfer due to convection implies that vapor is transported by airflow. This might be problematic in open-air ventilated crawl spaces, whereas when the ventilation brings humid air into the crawl space. The risk is especially high during summer, because it condensates due to a lower temperature in the crawl space.

Moisture in liquid state can transfer by the force of gravity, water overpressure, wind pressure, and capillary force (Nevander, 1994). Water overpressure induces a problem solely in basements, pools, and ponds, thus, not in the foundations included in this study. Wind pressure can wet the outside of the foundation during rain, but the surface should withstand this impact and dry. Nevertheless, the moisture can transfer from the surface by capillarity forces, yet considered a capillarity problem.

Gravity transfer occurs when water in and on ground a ground water is moving due to gravity forces. These problems are solved by forming the surface around the building correctly, as well as rainwater and drainage systems. These systems will be further examined in next chapter.

Moisture transfer due to capillary flow occurs because of the capillarity force. Capillarity force appears due to attraction forces between water molecules, a solid material and the surface tension in water. Due to this force, water is drawn into a porous material until it has reached the maximum height for capillarity rise in the specific material. The height of capillarity rise varies between materials, thus being higher in material with smaller pores, compared to those with big pores (Nevander, 1994). Hereby, water can rise above the ground water level and reach the foundation and base floor, because soil in general has a good capillary capability. Capillarity breaking layers between the building parts prevent capillarity problems. Under the foundation and base floor, the capillarity-breaking layer is made out of gravel without small particles. Between the foundation and the wooden superstructure, a capillarity breaking membrane is installed, usually made out of bitumen or cellular plastics (See Figure 4.) (RT 81-10854, 2005).

6.4 Ground draining and rain-water management

In the foundation construction the following aspects should be accounted for: rainwater from the roof, surface water on the ground from rain and melting snow and ground water, respectively, in addition to vetting the surface of the foundation. Firstly, the ground surface is formed leaning away from the building, in order to lead away the surface water from the building. According to the C2 (1998) this should be done by forming a three-meter deep area in a 1:20 slope outside the foundation wall (see Figure 12).

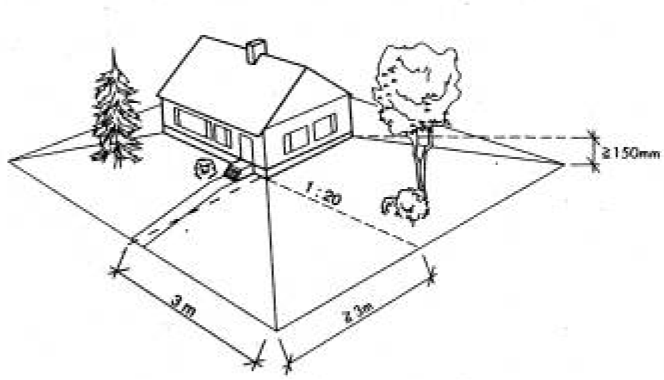

Figure 12. Slope around the building to lead away surface water (Sisäilmayhdistys ry., 2008)

Secondly, rainwater stemming from the roof has to be led down into a rain sewer placed in the ground. The rainwater system is built at the same time as the drainage system, thus, during the foundation phase. A rainwater system consists of rainwater-collectors under the pipes that lead the water down from the roof and pipes that lead it way from the building. (RIL 126-2009).

The water that is not led away by the slope or the rainwater system and ground water if present has to be led a way by a drainage system. The drainage system constitutes of drainage pipes and inspection pits. The drainage pipes are drawn outside the foundation perimeter, beneath the lowest level of the foundation structure. The pipes are embedded in a drainage gravel layer, which is interconnected with the capillarity-braking layer beneath the base floor. The gravel is furthermore forming a capillarity-breaking layer between the foundation and the ground soil. The gravel layer should also continue upwards to the ground surface, in order to form at least a 20 cm deep gravel layer beside the vertical foundation wall (C2, 1998). The drainage gravel should also be separated from other filling materials by a filter cloth (Nevander, 1994). Finally, the drainage system is connected to a pipe that leads the water to an open ditch or an infiltration field (RIL 126-2009).

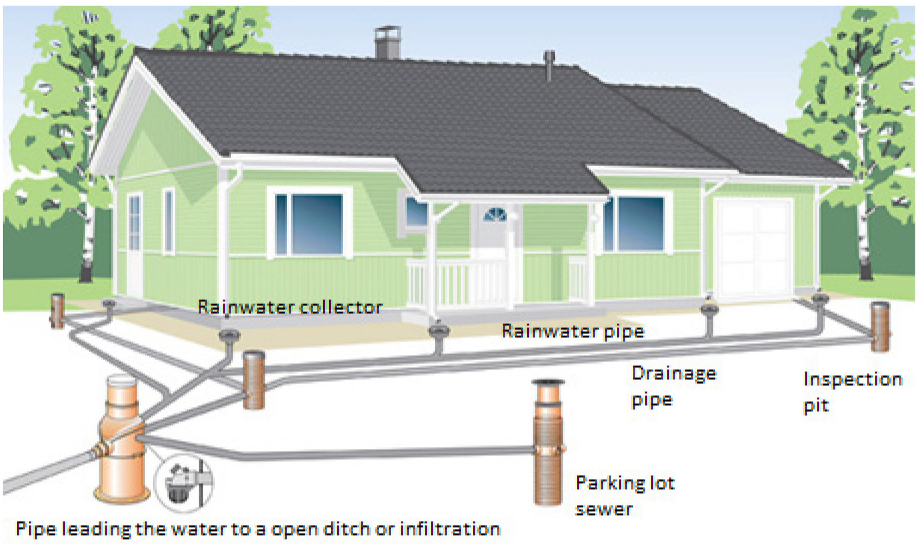

Figure 13. Drainage and rainwater system (www.rakentaja.fi, 2017)

Another important aspect concerning drainage and rainwater systems, is that the systems should be kept from freezing. However, this aspect will be examined in the ground frost chapter since it coheres with the ground frost insulation. The various designs of rainwater and drainage systems, and the slope around the building do not differ between the foundation alternatives, and therefore this cost will be excluded in the cost-analysis. The gravel usage can vary and will therefore be accounted for in the analysis.

6.5 Moisture protection in different foundations and base floor alternatives

6.5.1 Water insulation on foundation wall

Even if the foundation is above the ground water level, as is the case in non-basement buildings included in this study, the foundation has to be water insulated under the ground surface. The insulation method used in these buildings is called discontinuous water insulation. The method covers two separate parts: a foundation-wall-sheet on the vertical wall, and a bitumen membrane on the part of the footing sticking out from the wall and on the connection between the wall and the footing. The foundation-wall-sheet is installed by fasteners and the bitumen membrane is attached by heat to the surface. (RT 83-10955, 2009). This is an extra cost for foundation walls that has to be accounted for in the cost analysis, as this insulation is not needed in pillar foundations. In raft-slabfoundations, only the foundation-wall-sheet is needed, as the side of the foundation is solely vertical.

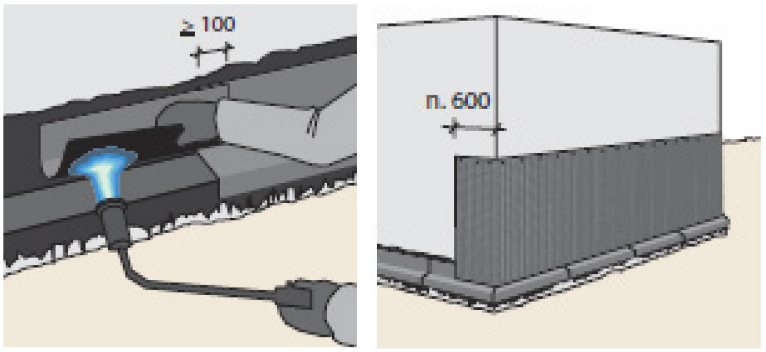

Figure 14. Bitumen-membrane insulation (left) and foundation-wall-sheet insulation (right). (RT 83-10955, 2009).

6.5.2 Moisture protection for concrete floors on ground

A CFG base floor requires a capillarity-breaking layer between the ground soil and the thermal insulation (Nevander, 1994). The thickness of the layer has to be at least 0,2 m (C2, 1998). In clay and silt ground, the layer has to be separated from the ground soil by a filter cloth (RT 81-11099, 2010). However, in this study these ground conditions are not considered, and therefore the filter cloth is excluded from the cost-analysis. Light-weight-clay-aggregate (LWA) has been used as a combination of thermal insulation and capillarity breaking layer in base floors before but due to its unpredictability, the use of this solution has declined (Nevander, 1994). Therefore, this solution will not be an alternative in this study.

Diffusion may cause problems in CFG base floors, due to the high humidity that can rise to 100% RH in the ground (Nevander, 1994). This can be avoided if the temperature difference is sufficient between the slab and the gravel beneath the thermal insulation that the slab is cast on (Nevander, 1994). The current minimum demands for thermal insulation for CFG base floors have to be checked, in order to meet the requirement for diffusion safety in CFG base floors.

6.5.3 Moisture mitigation in crawl spaces

If the relative humidity is too high in a crawl space, it might cause mold-growth. In a crawl space, there is always organic material, which is enough nutrients for mold-growth (Airaksinen, 2011). As mentioned before, the most critical time is during the summer, when humid air condensates due to the lover temperatures in the crawl space. To avoid moisture problems in the crawl space the following points are crucial: ventilation has to be sufficient; the temperature difference between the crawl space and outdoor air should not be too big in the summer; and water should not be able to accumulate in the crawl space (Nevander, 2014).

The ventilation openings in the foundation wall should be at least 0.4 percent of the base floor area, and twice as much in sections wall inside the crawl space (C2, 1998). To increase the temperature in the summer, it is recommended that the ground inside the crawl space be insulated (RT 83-11009, 2010). Airaksinen (2011) recommends that the ground is insulated with 300mm LWA or 50mm EPS, in order to manage the moisture. In addition, the ground beneath the insulation should be covered with at least a 200mm layer of drainage gravel that is connected to the drainage system (RIL 126-2009). If the ground is insulated with LWA, the gravel layer will be left out because LWA has both draining and insulating capabilities. The ventilation openings do not affect the cost, but the insulation and gravel layer do, and will therefore be accounted for in the cost-analysis.

The comparative cost analysis of the ground insulation in a crawl space is presented in Table 2. According to the calculation, it is clear that the EPS+gravel solution is the most cost efficient, and thus will be the only solution accounted for in further cost analyses.

Table 2. Comparative cost of ground insulation in crawl spaces (ROK, 2016).

Material	**Cost: work and material (€/m^2)**
EPS 50mm	5,04 €
Gravel 200mm	7,46 €
	Total cost: 12,50 €
LWA 300mm	17,10 €

In a completely open crawl space, that is a pillar foundation, the ventilation beneath the house works impeccably, and this brings the temperature in the crawl space to almost the same as the outdoor temperature (Nevander, 1994). This implies that the ground beneath the house does not have to be insulated in pillar foundations. Nevertheless, the topsoil has to be removed in order to make room for a 200mm capillarity-breaking layer in the pillar foundations, as well as to ensure that evaporation from the ground can be kept to a minimum (Nevander, 1994).

6.5.4 Foundations on bedrock

Although the bedrock has the load bearing capacity to have the foundation wall built directly on it, it is not executable in practice, since water can be trapped between the rock surface and the wall due to irregularities in the bedrock surface. Further, there would not be any capillarity-breaking layer between the foundation and the ground, which is not acceptable. Pillar foundations, on the other hand, can be built directly on the bedrock as the water can get away on each side of the pillar, and in addition, capillarity is not a problem since the open crawl space possesses such good drying possibilities.

7 Energy effiency in base floors

Heat transfer occurs due to heat conduction, radiation, and convection (Lienhard, 2017). In order to be energy efficient a building envelope has to be thermally insulated adequately, in order to stop energy losses due to heat conduction and radiation. In addition, the envelope has to be airtight to prevent energy losses due to heat convection. In practice, this implies that the base floor as a part of the envelope has to be insulated against thermal differences and be airtight. The amount of thermal insulation over different building parts is regulated in the national building code and is given as maximum heat transfer coefficients, or U-values. The level of airtightness over the buildings envelope is regulated in D3 (2012).

The U-value for base floors varies depending on the structural solution utilized. Base floors with a crawl space completely open to the outdoor, or a crawl space where the ventilation openings in the foundation wall is over 0.8 percent of the base floor area, need a U-value of U<0,09W/m2K. For crawl spaces where the openings are between 0.4 and 0.8 percent of the base floor area, the U-value is set to U<0,17 W/m2K. Base floors on ground need a U-value of U < 0,16 W/m2K. (RT 83-11009, 2010).

7.1 Heat convection

Energy losses due to heat convection occur, when an airflow transporting cold air through the buildings envelope i.e. draft or inside the structure itself i.e. internal convection (RIL 255-1-2014). Heat convection in base floors are usually prevented by an air barrier on the inside of the thermal insulation and by a wind protection on the outside (RIL 255-1-2014).

In an air-ventilated crawl space there has to be a wind protection on the outside of the thermal insulation, the purpose of which is to stop harmful air movements in the insulation i.e. internal convection (RIL 255-1-2014). Wind protection can be achieved using wood fiber boards, gypsum boards etc.. Nevertheless, the dominating solution in base floors is a 25mm wood fiber board (ROK, 2016). Due to their porosity, these boards increase the thermal insulation capability of the base floor (RIL 255-1-2014). As no convection can occur in hollow-core-slabs, and polyurethane boards they are wind-breaking layers as such, and there is no need for extra wind protection.

Raft-slab and HCS base floors are air barriers in itself as the foundation and base floor creates an uniform concrete slab in raft-slab foundations and the joint between the HCS and foundation walls are sealed with concrete. Concrete floor on ground that is cast separate from the foundation wall also gets an adequate air barrier due to the radon insulation membranes that are sealing the joints.

In a wood framed base floor, the air barrier consists of either a paper or plastic membrane. The plastic membrane is also called vapor barrier because it is also act as barrier for moisture diffusion. If the air barrier has to be both an air and vapor barrier depends of the characteristics of the other structural materials in the base floor, but usually mineral wool insulated wooden base floors need the vapor barrier and base floors insulated with wood fiber insulation get a sufficient air barrier with a paper membrane. If polyurethane insulation is used in wood framed base floors no extra air barrier is needed. (RIL 255-1-2014).

7.2 Thermal insulation materials

Thermal insulations materials are mineral wool, expanded polystyrene (EPS), wood fiber insulation, extruded polystyrene (XPS), Polyurethane etc. (RIL 255-1-2014). According to the cost-data literature, mineral wool and wood fiber insulation are the most common thermal insulating materials in base floors with a wooden frame. Polyurethane insulation bears a much lower heat transfer coefficient than the other insulation materials, and therefore the insulation layers can be thinner and consequently the height of the base floor structure (RIL 255-1-2014). In the literature, it is evident that EPS is the dominating insulation material in base floors on ground and base floors made out of hollow-core slabs (ROK, 2016). Due to the existing cost data, the thermal insulation materials used in the cost analysis are going to be mineral wool, wood fiber insulation, polyurethane, and EPS.

7.3 Evaluation of thermal insulation materials

In wood framed base floors with a U-value of 0,17 W/m2K, a 275mm mineral wool or wood fiber insulation plus 25mm wood fiber board is required (RT 83-11009, 2010). For a U-value of 0,09 W/m2K the insulation thickness required is ca. 490mm plus the 25mm fiber board (www.ekovilla.com, 2017). The wood fiber insulation is undoubtedly a more cost-efficient solution than the mineral wool, according to the cost data. A 275mm insulation layer made of wood fiber has a cost of 15.91 €/m^2, compared to the cost of mineral wool, which is 31.16 €/m2 for the same thickness (ROK, 2016). This implies that the mineral wool solution can be excluded already at this stage, to the advantage of wood fiber insulation in the final cost estimation.

In addition, the use of polyurethane boards will be analyzed even though the cost is higher compared to the other alternatives (ROK, 2016). However, cost savings will occur due to the smaller depth of both the insulation layer and the wood frame. The thickness needed for polyurethane is 320mm in an open base floor, and 160mm in a base floor with ventilation opening between 0.4 and 0.8 percent of its area. In concrete floor on ground (CFG) and HCB, a 120mm layer of polyurethane insulation is required. (www.kingspaneristeet.fi, 2017).

Hollow-core-slab base floors fulfill the 0,17 W/m^{2}K demand with 200mm EPS insulation on top of it, or 220mm beneath it. Nevertheless, the solution with insulation beneath the HCS was proven the most cost-effective solution already in chapter 4. In CFG base floors the 0,16 W/m^{2}K demand is achieved by a 200mm insulation in the perimeter area (RT 83-11009, 2010). In the center area of a building, the heat transfer demand could be met by 100mm EPS, yet the moisture diffusion safety demand calls for 200mm in the center area as well (Nevander, 1994).

Table 3. Comparative cost of thermal insulation in HCS and CFG base floors (ROK, 2016).

Structure	Insulation material	Cost: labor and material (€/m^2)
HCS	EPS 220mm	18,15 €
HCS	Polyurethane 120mm	23,17 €
CFG	EPS 200mm	16,23 €
CFG	Polyurethane 120mm	23,17 €

In table 2, the result of a comparative cost analysis of thermal insulation in HCS and CFG base floors is presented. It shows a clear cost difference between EPS and polyurethane insulation in both cases. Therefore, the EPS insulation is the only material used in further analyses of these structures.

8 Ground frost

Ground frost is a phenomenon that occurs during the cold period of the year, when the water in the ground soil freezes and the soil expands. The ground frost can damage structures due to movements, applied forces or changing the characteristics of building materials. The main methods used to protect structures against ground frost include ground frost insulation, aggregates that not expand when freezing or make the foundation reach a frost-free depth. (RIL 261-2013).

8.1 Ground frost insulating materials

Ground frost insulation materials are EPS, XPS, and LWA (RIL 261-2013). Of these three, have cost data have only been found for EPS and LWA. EPS has a lower heat transfer coefficient than LWA, or 0,043 W/mK respectively 0,16 W/mK (RIL 261-2013). Thus, the LWA requires a thicker layer in order to protect as good as a thinner EPS layer. On the other hand, LWA possesses draining capabilities as such, whereas the volume that differs between the LWA and EPS layers, has to be filled with additional drainage gravel in the EPS alternative. Thereby, when comparing these two materials, the extra gravel needed in the EPS case has to be accounted for.

Table 4. Comparative cost-analysis of ground frost insulation materials (ROK, 2016).

heat transfer resistance (m^2K/W)	Materials	Cost (€/m^2)	Material	Cost (€/m^2)
1,16	EPS 50mm	6,05	LWA 190mm	11,01
	Gravel 140mm	5,22		
	tot.	11,27		
1,62	EPS 70mm	7,69	LWA 260mm	15,06
	Gravel 190mm	7,09		
	tot.	14,78		
2,33	EPS 100mm	10,1	LWA 375mm	21,72
	Gravel 275mm	10,26		
	tot.	20,36		

The comparative cost-analysis of the ground frost insulating materials shows no major difference between the materials from a cost perspective. Thus, both materials are considered equal alternatives from a cost perspective. This gives the freedom to choose the material based on which material is preferred to work with. However, in the present study the cost analysis is made using EPS as ground frost insulation material, since the there is no reason to make two different calculations giving the same result.

8.2 Design of ground frost protection

Permanently heated building, like those examined in this study, shall be designed to the highest cold content repeated under a 50-year period (RIL 261-2013). The cold content varies in the country, as is evident in Figure 15. Because this study focuses on buildings in the southern parts of Finland, the cold content of 40000 Kh will be adopted for the analysis. The ground frost protection has to be designed together with the design of the thermal insulation in the base floor (RT 81-10854, 2005).

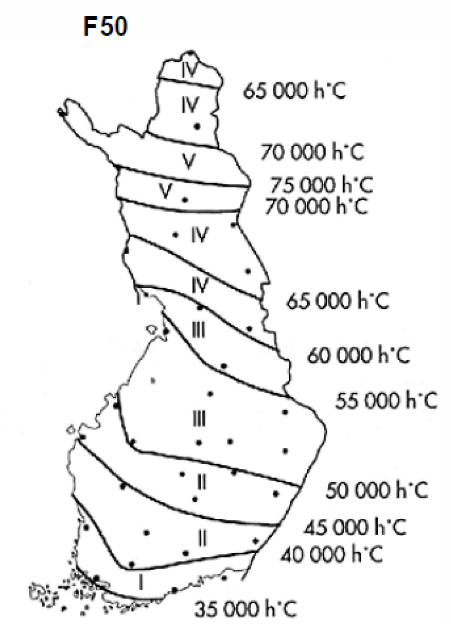

Figure 15. Cold content during 50-year period in Finland (RT 81-10590, 1995).

In the ground frost protection design it is assumed that the ground is free from snow. The depth of ground frost depends on the cold content and the soil materials. In this study, where firm soils are analyzed, the frost-free depth is 2,4m. There are coarse soils that do not expand when freezing and therefore no ground frost protection is needed. Anyhow, this is so uncommon that it is assumed that ground frost protection is needed. Bedrock does not expand due to freezing. (RIL 261-2013). The design of the ground frost protection in this study will be made according to the methods presented in the book RIL 261-2013.

8.2.1 Ground frost protection in heated buildings

To determine the amount of insulation needed, the heat resistance and the structural method of the base floor (crawl space or CFG) have to be known. The indoor temperature is assumed to be at least +17 Celsius. The foundation wall has to be well insulated (as the walls chosen in chapter 4 are), and the underside of the base floor insulation has to be under 0,6 m from the ground level on the outside. Thereafter, the thickness and width (width of insulation outside the edge of the footing) of the ground frost insulation are chosen from tables and diagrams based on the input values. Crawl spaces and CFG have different diagrams and in case a crawl space base floor has higher heat resistance than 6,25 m^2K/W, frost insulation has to be considered inside the crawl space or it has to be designed as a cold building. (RIL 261-2013).

8.2.2 Ground frost protection in cold buildings

Ground frost protection should be designed for cold building if no heating is present in the building, or the temperatures in the crawl space is very low (RIL 261-2013). In this study, only the pillar foundation requires a design according to a cold building. The same input as in the heated buildings is needed, except for the heat resistance of the base floor. The insulation layer is recommended to be situated under the footing. Further, the medium temperature of the year is needed, which for the present study focusing on on southern Finland,is assumed to be +4 Celsius. By applying the distance between the insulation and the ground surface, the width of the insulation is determined by a diagram as well. In addition, the needed insulation thickness is chosen from a diagram as well. (RIL 261-2013).

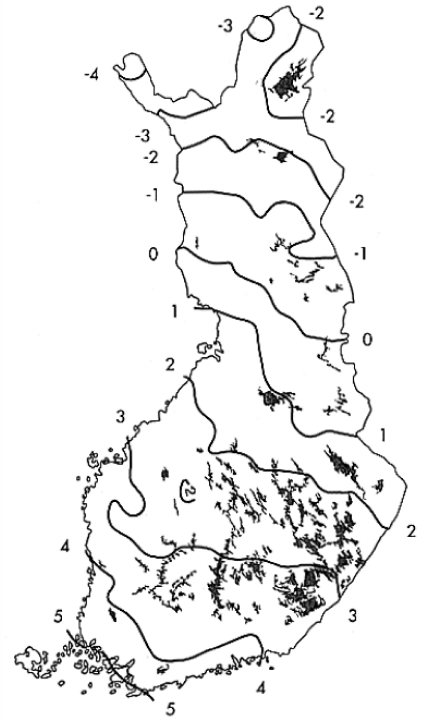

Figure 16. Medium temperatures of the year in Finland (RT 81-10590, 1995).

8.2.3 Ground frost protection for water pipes

Rainwater, sewer, drainage, and water pipes should be kept from freezing (RIL 261-2013). In pillar foundations, rainwater and drainage are allowed to freeze, as the base floor in this case do not suffer in case there is a little extra water on the ground for a limited period of time (Nevander, 1994). However, the sewer and water pipe are never allowed to freeze, as it is nowadays intolerable to accept breaks in the water supply. As the border of this cost-analysis is drawn where the ground frost insulation ends outside the building, the only protection for water and sewer pipes that has to be accounted for lies under the base floor. In all base floors, except the one with a pillar foundation, the cold cannot reach the pipes, since in CFG they are covered by earth and in crawl spaces they are covered by the ground insulation.

Therefore, the sewer and water pipes are in need of extra protection in a pillar foundation, in order to be comparable to the other alternatives. The problem can be solved by installing the pipes in a sand filled box made of insulation material (RIL 261-2013). A formula will be created that assume the cost of this arrangement, which will be added to the cost of a pillar foundation in the development phase. According to a diagram in RIL 261-2013, this box can be designed to be 0,6m deep and 0,4m high and made out of 100mm EPS on all sides. This calls for 1,60m^2 of 100mm EPS insulation per distance meter box. It can be assumed that the box is filled with gravel at the same time as the other fillings, and therefore it is unnecessary to account for gravel in the box in the formula. It will be assumed that the box has to be y/2 meters long under the base floor and the cost of 1,60m^2 100mm EPS is 13,5 €/m (ROK, 2016). Then the pipe box cost is calculated by equation 3. below. In cases where the bedrock comprises the surface, a

1,0m wide and 0,7m deep channel has to be mined and this cost is added to the equation in these cases. The cost of 1,0 m^2 (has to be calculated for a little bit more, as mining is not very exact) channel mining is 70€/m, and 37,32 €/m for gravel filling in the channel, as well as 296€ for placing of mining mats assuming that mining will be done in 4 hours (ROK, 2016). The cost of channel mining can vary between 30 and 70€ per cubic meter (ROK, 2016), but although the amount of mining is very small in these cases, the mobilization cost of the mining contractor is still the same. Therefore, it is reasonable to assume that the cost per cubic meter will be the highest or 70€/m^3 respectively.

Equation 3. Total cost of a water pipe box in a pillar foundation (y=depth of building).

Cost of water pipe box (€) = (y/2)*13,5+in case of mining (y/2)* 107,32+296

By algebraic simplification, the equation can be written as following:

Cost of water pipe box (€) = 6,75y + in case of mining 53,66y + 296

This cost will be added as a part of the total cost of a pillar foundation in the cost comparisons.

In the other foundation solution, where the rainwater and drainage pipes are not allowed to freeze, the pipes are usually installed and protected under the ground frost insulation installed around foundation (RIL 261-2013). The minimum depth in southern Finland for unprotected drainage pipes are 0,8m and 1,5m for rainwater pipes (RT 81-11000, 2010). Even if a foundation is built on bedrock (non-freezing), except for pillar foundation, the foundation has to be insulated as much as if it is built on soil to prevent that the drainage and rainwater pipes from freezing.

9 Cost evaluations of alternatives

In this chapter, the cost evaluations that have not been done before will be made. These evaluations are crucial in order to present the alternatives that will be combined in the development phase. So far, foundation wall elements and built-in place foundation walls have been evaluated in chapter 4. In addition, the ground insulation alternatives have been evaluated in chapter 6. In chapter 7, polyurethane and EPS insulation materials were evaluated for HCS and CFG base floors. And last, the ground frost insulating materials LWA and EPS were evaluated in chapter 8.

In this section, the cost-efficiency of different foundation depths are evaluated. In addition, a formula for mining costs will be created. Finally, the different foundation and base floor alternatives, which are used in the cost-comparisons in the development phase, are presented.

9.1 Evaluation of cost-efficiency of foundation depths

To be able to evaluate the most cost-efficient foundation depth, the cost of excavation, foundation wall or pillar length, gravel fillings, and ground frost insulation have to be taken into account, as they vary with the foundation depth. The structures that have varying foundation depth are the LWC-foundation wall and the pillar foundation.

As the foundation depth is increased, the cost of ground frost insulation declines, while the cost of excavation, gravel fillings, foundation walls and pillars increases. First, the cost development of a LWA- foundation wall with an increasing foundation depth will be analyzed. The foundation will be analyzed both with a crawl space and a CFG base floor, as the amount of ground frost insulation differs. In Table 5. is the cost for both cases is presented, that is with a foundation depth of 0,5m and 0,75m, respectively. It is assumed that the excavation ditch for the foundation has to be 2m wide and 0,2m below the footing. The cost of gravel is only added for the deeper alternative, as the difference in gravel usage compared to the shallower alternative, as it is enough for comparing the alternatives to each other. The cost of the footing is not accounted for, as it does not change with the foundation depth. The cost is given as € per distance meter foundation. Only the cost that differs with the foundation depth is accounted for in the comparison.

Table 5. Evaluation of cost-efficiency for a LWA-foundation wall with different foundation depths.

LWA- foundation wall with CFG base floor				**LWA-foundation wall with crawl space**			
Foundation depth: 0,5m		Foundation depth: 0,75m		Foundation depth: 0,5m		Foundation depth: 0,75m	
Cost source	Cost, €	Cost source	Cost, €	Cost source	Cost, €	Cost source	Cost, €
Gravel	0	Gravel	3,73	Gravel	0	Gravel	3,73
EPS 70mm	8,47	EPS 50mm	6,05	EPS 100mm	12,10	EPS 100mm	12,10
Excavation	11,71	Excavation	15,88	Excavation	11,71	Excavation	15,88
Wall, h=800mm	78,52	Wall, h=1050mm	103,09	Wall, h=800mm	78,52	Wall, h=1050mm	103,09
Total cost:	**98,70**	**Total cost:**	**128,75**	**Total cost:**	**102,33**	**Total cost:**	**134,8**

The results are unambiguous when adjusting the foundation depth for a LWC-foundation wall with a concrete floor slab. The cost rises with 30,4% already by increasing the foundation depth from the minimum of 0,5 m to 0,75 m. The reason behind this is that it is much more expensive to make the wall higher, than are the savings are for decreasing the amount of ground frost insulation. This in turn, implies that on building lots where bedrock is not close to the surface, or have at least 0,7 m of soil on top of it, the minimum foundation depth of 0,5 m is the most cost-efficient solution for a foundation wall. Similar conclusions can be drawn for the crawl space solution, since the increased foundation depth increases the cost by 31,7%. The crawl space solution makes the insulation thickness rise from 70mm to 100mm for the minimum foundation depth, compared to the one with concrete floor on ground. When the foundation depth is adjusted to 0,75 m, the insulation thickness does not shrink so much that a thinner board can be applied.

Furthermore, the EPS-form element outperforms the LWC-foundation wall when comparing cost. The EPS-form element cannot adjust its foundation depth and is therefore 0,5m. With the foundation depth of 500mm, the LWC-foundation has a cost of 189,52€/m, which is a 35,6% higher cost than the 139,74€/m for the EPS-form element foundation (ROK, 2016). Therefore, the only foundation wall alternative used in further calculations, is the EPS-form element.

Pillar foundation on soil becomes most cost-efficient if constructed without ground frost insulation, so that the foundation depth is 0,8 m and that there is a 1,5 m thick layer of non-expanding material beneath the footing. In Table 6. the comparative cost of the cheapest pillar foundations on soil is presented, with and without ground frost insulation, respectively. The two alternatives have been found through iteration. The comparative cost values show that a ground frost insulated pillar is 65% more expensive than a pillar without insulation. Thereby, pillar foundations on soil will be considered to be built without insulation in further examinations.

Table 6. Comparative cost of pillar foundations on soil (ROK, 2016)

Pillar foundation with ground frost insulation		Pillar foundation without ground frost insulation	
Cost source	**Cost (€)**	**Cost source**	**Cost (€)**
Gravel, 1,8m3	63,44	Gravel, 2,7m3	67,18
EPS 100mm, 9m2	90,9		
Footing	26,7	Footing	26,7
Pillar, h=1600mm	65,56	Pillar, h=1400mm	57,37
Excavation	97,8	Excavation	57,68
Total cost:	**344,06 €/pillar**	**Total cost:**	**208,93 €/pillar**

On bedrock, pillars can be built directly on bed rock without ground frost insulation, footings, and with less gravel fillings. Table 7. presents the comparative costs of pillars directly attached to the bedrock, with the bedrock on different elevations.

Table 7. Comparative cost of pillar directly attached to the bedrock (ROK, 2016)

Bedrock level	Pillar length, h	Pillar cost (€)	Gravel cost (€)	Excavation cost (€)	Total cost (€)
0m	800mm	32,78	0	0	**32,78**
0,7m	1500mm	61,46	39,19	17,56	**118,21**
1,2m	2000mm	81,95	67,18	30,1	**179,23**
1,4m	2200mm	90,145	67,18	35,11	**192,44**
2,1m	2900mm	118,83	67,18	52,67	**238,68**

The comparative cost of pillars attached directly to the bedrock demonstrates that it is not feasible to attach pillars to the bedrock, when the bedrock is deeper than 1,4 m. Thus, if the bedrock is deeper than 1,4 m, pillars should be built in the same way as it is on pure soil.

If the raft-slab or foundation wall is built where the bedrock is at the surface, an area that is at least 0,7m deep and extending 1 m outside the perimeter of the house has to be mined. The cost of mining is 60€/m^3, with and additional cost of the placement of mining mats that is 74€/h (ROK, 2016). Assuming that the mining occurs during 8 hours, the cost for mining the whole foundation is calculated by the equation below. The x and y are the length and depth of the building, respectively.

Equation 4. Mining costs for mining under the whole building.

Mining cost (€) = (x+2)*(y+2)*0,7*60+592

The different solutions that will be combined with base floor alternatives are presented in Table 4.

9.2 Foundation alternatives for further development

The cost of the foundations will be given in form of € per distance meter foundation. The cost value includes both material and labor costs. In the tables below, all costs for a foundation are enumerated, except for the mining cost.

Table 8. Total cost of a foundation wall foundation with CFG (ROK, 2016).

Cost source	Cost €/m
Excavation	11,71
Bitumen membrane on top of wall	3,99
EPS-form element, concrete and bracings	78,25
Ground frost insulation, EPS 70mm	8,47
Gravel fillings	37,32
Total cost:	**139,74 €/m**

Table 9. Total cost of a foundation wall foundation with crawl space (ROK, 2016).

Cost source	Cost €/m
Excavation	11,71
Bitumen membrane on top of wall	3,99
EPS-form element, concrete and bracings	78,25
Ground frost insulation, EPS 100mm	12,10
Gravel fillings	37,32
Total cost:	**143,37 €/m**

Table 10. Total cost of a raft-slab foundation (ROK, 2016).

Cost source	Cost €/m
Excavation	11,71
Bitumen membrane on top of foundation	3,99
Concrete, formwork, EPS	107,84
Foundation-wall-sheet	3,97
Ground frost insulation, EPS 70mm	8,47
Gravel fillings	37,32
Total cost:	**173,3 €/m**

For pillar foundations, the cost of two combined 51x400mm wood beams between the pillars has to be accounted for in the total foundation cost and that the pillar distribution is 3000mm.

Table 11. Total cost of a pillar foundation on soil (ROK, 2016).

Cost source	Cost €/m
Excavation	19,23
Bitumen membrane on top of pillar	0,52
Pillar	19,12
Footing	8,90
Gravel fillings	22,39
Wood beam, 2*51x400mm	43,9
Total cost:	**114,06 €/m**

The cost of a pillar foundation attached to bedrock will be similar to the cost evident in Table 7, but divided by 3m, and with the cost of the wood beam and bitumen membrane added as well. Table 12 presents the total cost of pillar foundations attached to bedrock.

Table 12. Total cost of a pillar foundation attached to bedrock (ROK, 2016).

Bedrock level	Total cost €/m
0m	**55,35**
0,7m	**83,82**
1,2m	**104,16**
1,4m	**108,57**
2,1m	**123,98**

All foundation alternatives available have now been presented above, in Tables 8 to 12. In the development phase, the total cost of the foundations presented in the tables will be connected to base floor solutions.

9.3 Evaluation of base floor alternatives

There will be three base floor alternatives to be be combined with the foundation alternatives from the previous sector, in development phase. These base floor solutions are a wooden base floor for pillar foundations, a base floor above a crawl space, and a concrete floor on ground. Next, these base floor alternatives will be evaluated, before the total cost of each base floor can be given. The base floor costs will be given in form of € per square meter base floor.

9.3.1 Wooden base floor slab for pillar foundations

There are two different alternatives to build a wooden base floor for a pillar foundation. The first one has wood fiber insulation and requires a height of the wood frame equivalent to 500mm, whereas the second alternative with polyurethane insulation only requires a 400mm high frame. Both structures have a beam distribution of 600mm. In addition, both have the same structure on the top, that is veneer and a floor slab. Therefore, only the underlying structure has to be compared first, which is done and presented in Table 13.

Table 13. Cost comparison of a base floor for pillar foundations with different insulation materials (ROK, 2016).

Base floor insulated with wood fiber		Base floor insulated with polyurethane	
Cost source	**Cost (€/m2)**	**Cost source**	**Cost (€/m2)**
Wood fiber insulation, 490mm	26,88	Polyurethane, 320mm	63,79
Secondary wood beam layer, 48x198mm	9,92	Wood beam, 51x400mm,	38,16
Wood beam, 51x300mm + air barrier+ wind protective board	45,17		
Total cost:	**81,97 €/pillar**	**Total cost:**	**101,95 €/m2**

The comparative cost of the polyurethane insulated structure is 101,95 €/m2 and the cost of wood fiber insulated is 81,97 €/m2. Thereby, the wood fiber insulated floor is chosen for the pillar foundation. The total cost is presented in Table 14.

Table 14. Total cost of wooden base floor for pillar foundations (ROK, 2016).

Cost source	**Cost €/m2**
Wood fiber insulation, 490mm	26,88
Secondary wood beam layer, 48x198mm	9,92
Wood beam, 51x300mm + air barrier+ wind protective board	45,17
Veneer board, 18mm	20,01
Concrete floor slab, 60mm	22,39
Ground insulation and top soil removal	15,21
Total cost:	**139,58 €/m2**

9.3.2 Base floors above crawl space

The self-supported base floor above a crawl space with foundation wall can be either be HCS, or a wood framed base floor. The total cost of these two alternatives is presented in Table 15.

Table 15. Total cost of base floors supported by a foundation wall (ROK,2016).

Wood frame insulated with wood fiber		HCS insulated with EPS	
Cost source	**Cost (€/m2)**	**Cost source**	**Cost (€/m2)**
Wood fiber insulation, 275mm	15,91	EPS, 220mm	18,15
Ground insulation and top soil removal	15,21	Ground insulation and top soil removal	15,21
Veneer board, 18mm	20,01	Concrete floor slab, 40mm	14,10
Concrete floor slab, 60mm	22,39	HCS, 200mm	49,28
Wood beam, 51x300mm + air barrier+ wind protective board	45,17		
Total cost:	**118,69 €/m2**	**Total cost:**	**96,74 €/m2**

The wooden base floor above crawl spaces has a total cost of 118,69 €/m2, compared to the hollow-core-slab base floor, which has a total cost of 96,74 €/m2. Thereby, the wooden base floor above the crawl space can be eliminated from the further analysis, since it is a more expensive alternative than the hollow-core-slab alternative.

9.3.3 Concrete floor on ground

The concrete slab on top of thermal insulation and the capillarity-breaking layer has a total cost of 48,56 €/m2. Further, the radon ventilation system must be remembered when using this structure together with a foundation wall. The same structure applies for the raft-slab foundation as well. The total cost calculation for this base floor structure is presented in Table 16.

Table 16. Total cost of concrete floors on ground (ROK, 2016).

Cost source	Cost €/m2
Concrete floor slab, 80mm	20,80
EPS, 200mm	16,23
Capillarity-breaking layer, 200mm	8,82
Top soil removal	2,71
Total cost:	**48,56 €/m2**

10 Development phase

In this phase, the different foundation and base floor alternatives will be combined, following the combination scheme presented in Table 1. Subsequently, the formulas will be developed, by which a comparative cost value can be calculated. This is made by giving measurements to variables x and y, that is, the length and depth for the building, respectively.

The formulas will be completed by using the cost of the radon ventilation system for base floors with separate cast CFG, water pipe box for pillar foundations, the mining channel for pillar foundations built where bedrock is directly in the surface and the mining cost for the other foundations built on lot with bedrock in the surface. The combinations used are the following:

1. Foundation wall with a concrete floor on ground and the RVS.
2. Foundation wall with a hollow-core slab base floor.
3. Raft-slab.
4. Pillar foundation with wooden base floor.

The formulas will be given for three different scenarios. The first one will be when bedrock on level of at least 1,4m below the surface. In this scenario, the pillar foundation will not be attached to the bedrock and no mining will occur at all. In the second scenario bedrock is present in the surface and mining costs will occur. The last scenario is the case where bedrock is near the surface but deep enough to avoid mining.

The formulas will then be plotted in a bar chart, with square meters on the horizontal axis, beginning with 30 m2 and continuing with an increase of 20m2 at a time until it reaches 210 m2. The vertical axis shows the cost of the four combinations for buildings with the same shape, but different areas. Two different shape types will be tested: one quadratic i.e. x is equal to y; and one rectangular i.e. x=1,5y. Thereafter, the results will be analyzed from the charts and conclusions will be drawn about cost behavior of the different combinations. When the conclusions have been drawn, a decision making model will be created as the final step in this chapter, by which the most cost-efficient foundation and base floor combination can be chosen for different scenarios.

10.1 Foundations supported solely by soil

1. Foundation wall with a concrete floor on ground and a RVS:

Comparative cost = 2*(x+y)*139,74+(x*y)*48,56+12,56x + 12,56y + 994,11

2. Foundation wall with hollow-core slab base floor:

Comparative cost = 2*(x+y)*143,37 +(x*y)*96,74

3. Raft-slab

Comparative cost = 2*(x+y)*173,30 +(x*y)*48,56

4. Pillar foundation with wooden base floor and the water pipe box (notice that an extra row of pillars has been added in order to support the base floor):

Comparative cost = (3x+2y)*114,06+ 6,75y+(x*y)*139,58

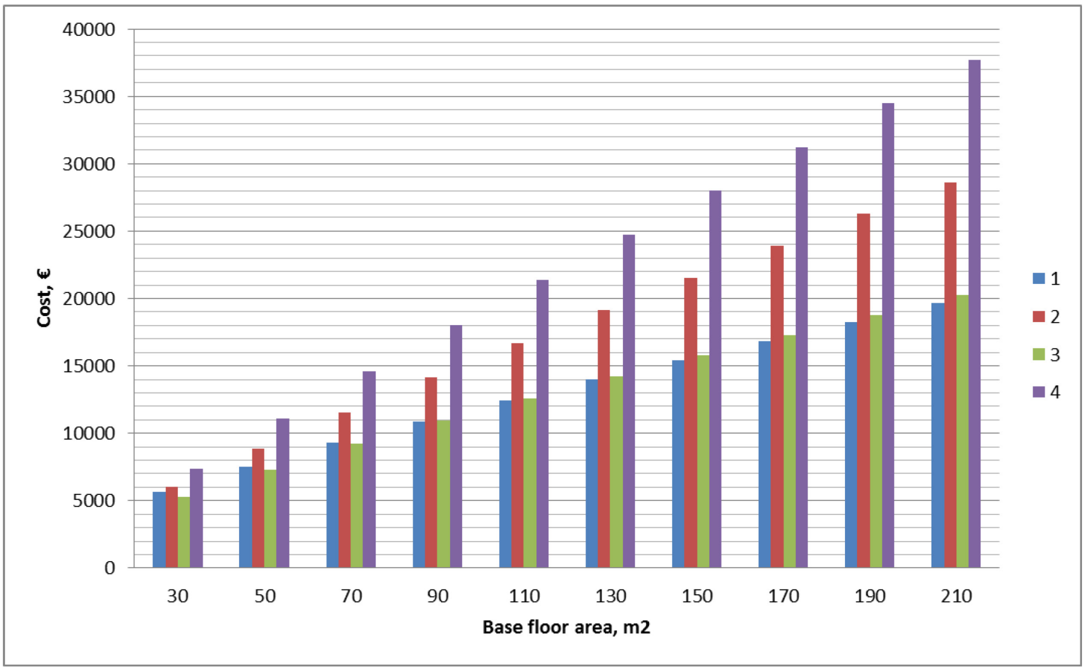

Figure 17. Cost comparisons of foundation and base floor combinations for a building with a quadratic shape (x=y), founded on soil.

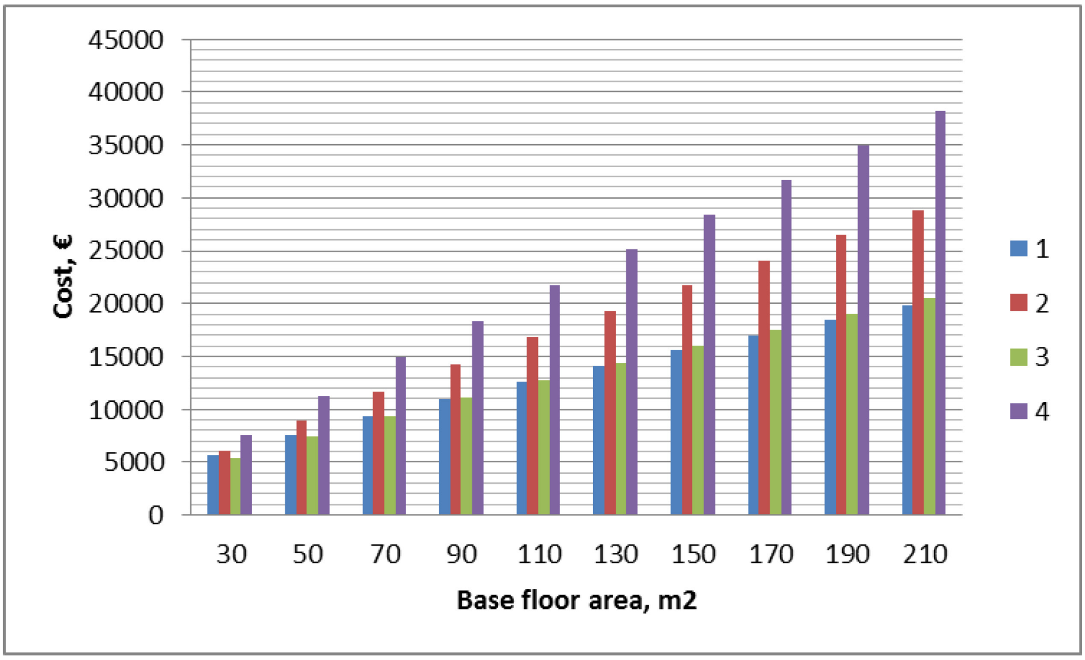

Figure 18. Cost comparisons of foundation and base floor combinations for a building with a rectangular shape (x=1,5y), founded on soil.

Based on Figure 17 and 18, it can be concluded that a pillar foundation is the least cost-efficient solution in all cases, when bedrock is not close by. The foundation wall with the HCS is more expensive as well, compared to combination 1 and 2, and can neither be regarded the most cost-efficient solution. The differences between the combinations 1 and 2, and 3 and 4, respectively, become bigger as the building grows. The combinations 1 and 2 have almost the same cost during the whole interval. The raft-slab foundation base floor has a small edge over alternative 1, until the size of the building area grows beyond 70m2. After 70m2, the fixed cost of the RVS in alternative 1is made up by the slightly more expensive variable cost in combination 2.

10.2 Bedrock present in the surface

When the bedrock is present in the surface, mining has to be done underneath the whole building for all combinations, except for the pillar foundation, where only a channel for a water pipe box must be mined. The same shapes and building areas as in the previous section will be analyzed. However, the only difference for the formulas for combination 1 to 3 is the mining cost, which is the same for these alternatives. Thereby, it is a satisfying solution to only calculate the cost for combination 1, since by pure logic, combination 2 will still be more expensive than combination 1, and combination 3 will follow the same pattern as in the previous chapter, that is, it will be almost the same as combination 1. The formulas for this case are the following:

1. Foundation wall with a concrete floor on ground, a RVS and mining costs:

Comparative cost = 2*(x+y)*139,74+(x*y)*48,56+12,56x + 12,56y + 994,11+(x+2)*(y+2)*0,7*60+592

4. Pillar foundation with wooden base floor, the water pipe box and channel mining:

Comparative cost = (3x+2y)*55,35+ 6,75y+(x*y)*139,58+ 53,66y + 296

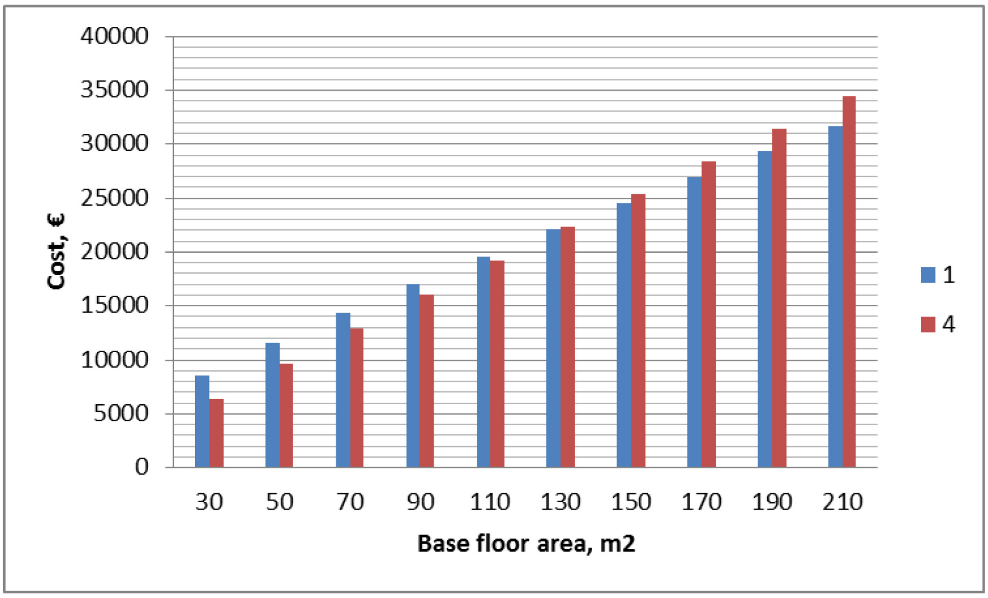

Figure 19. Cost comparisons of foundation and base floor combinations for a building with a quadratic shape (x=y), when bedrock is present in the surface.

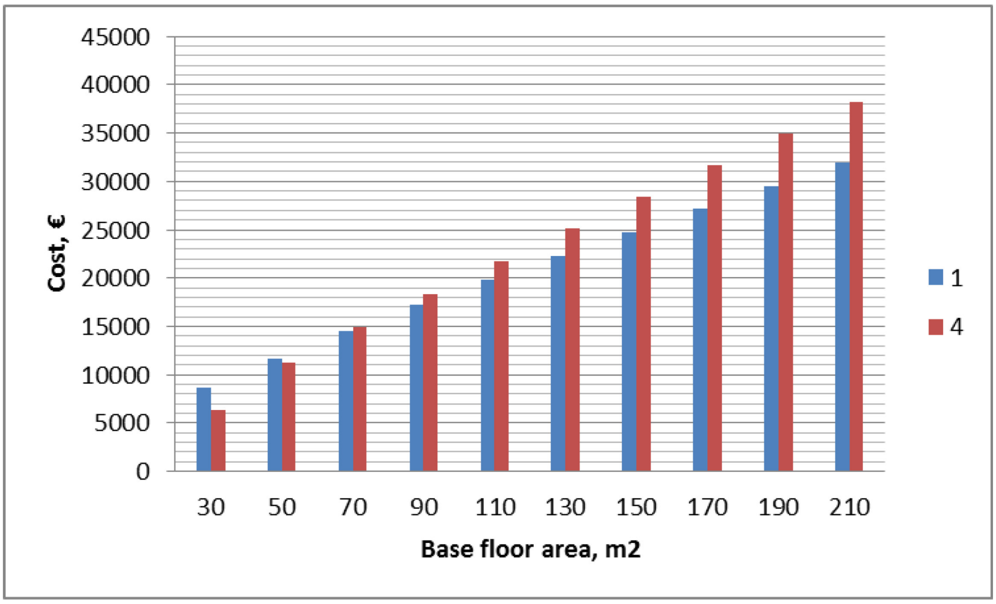

Figure 20. Cost comparisons of foundation and base floor combinations for a building with a rectangular shape (x=1,5y), when bedrock is present in the surface.

Comparing Figures 19 and 20 with Figures 17 and 18, it is evident that a building lot with rock in surface always comprises a more expensive alternative to build on, in comparison with a lot without bedrock in the surface. Even if the pillar foundation is very inexpensive, since it can be attached directly to bedrock, it cannot compensate for the relatively expensive base floor with which it is combined. This is the case in smaller buildings as well, where the base floor area is small compared to the foundation perimeter.

Nevertheless, if the building lot is already acquired, and bedrock is present in the surface cost-saving decisions can still be done. The pillar foundation is cheaper than combination 1 until the base floor area reaches the size of 130m2, and a cost break-even between alternative 1 and 4 occurs. If the base floor area increases from 130m2, combination 1 is the most cost-efficient solution from there on.

10.3 Bedrock near the surface but mining can be avoided

In this section, the bedrock level is assumed to be 0,7m below the ground surface. This means that neither mining for combination 1, nor channel mining for combination 4 must be executed. For the same reasons as in the previous chapter, combination 2 and 3 does not have to be analyzed again. Nevertheless, the pillars in combination 4 can be attached directly to the bedrock. The formulas will be the following:

1. Foundation wall with a concrete floor on ground and a RVS (this formula is the same as in section 10.1):

Comparative cost = 2*(x+y)*139,74+(x*y)*48,56+12,56x + 12,56y + 994,11

4. Pillar foundation with wooden base floor, the water pipe box and the pillars are attached directly to the bedrock:

Comparative cost = (3x+2y)*83,82+ 6,75y+(x*y)*139,58

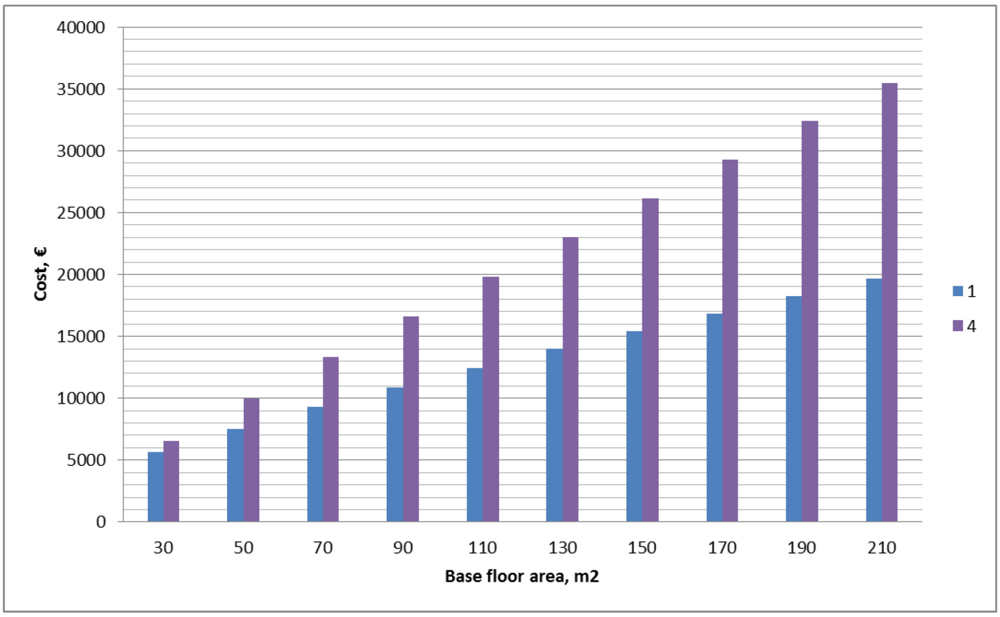

Figure 21. Cost comparisons of foundation and base floor combinations for a building with a quadratic shape (x=y), when bedrock is 0,7m below the surface.

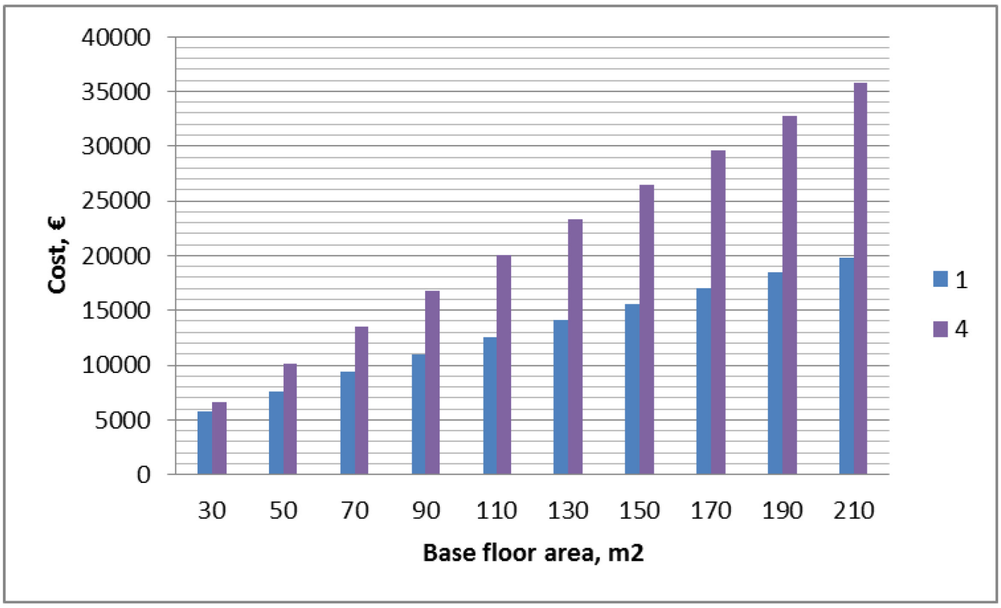

Figure 22. Cost comparisons of foundation and base floor combinations for a building with a rectangular shape (x=1,5y), when bedrock is 0,7m below the surface.

From the two figures above, the conclusion can be drawn, that if no mining has to occur, the pillar foundation, that is combination 4, is always more expensive than combination 1. This is manifest whether the base floor area is very small or whether the shape of the building is altered. This will be the last cost comparison included in this study, since the fact that pillar foundations are more expensive, compared to foundation wall foundations with a CFG base floor, is indisputable. If the bedrock level gets lower than 0,7m, the cost of the pillar foundation will only get more expensive, whereas the cost of the other combinations will remain the same.

10.4 Model for decision-making

The model for decision-making can be used to guide decision makers in small house projects, towards the most cost-effective foundation and base floor combination. The model, which is presented as a flow chart, can affect the decision making regarding which building lot that should be acquired, as well as affect the decisions made when the lot has been acquired.

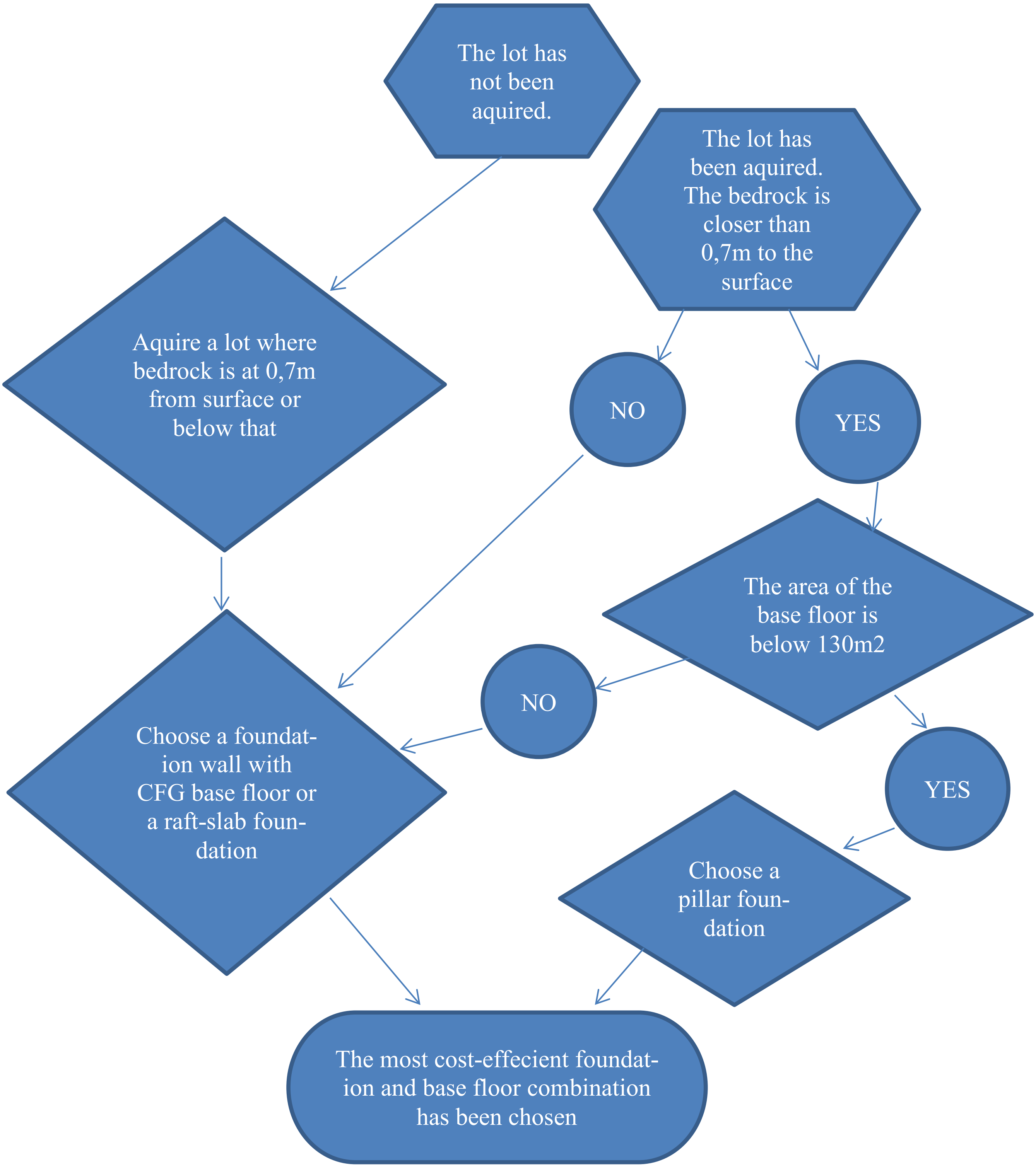

Figure 23. Decision-making model for choosing foundation and base floor combinations.

The decision making model is very simple to use. If the lot is not acquired yet, a lot with bedrock at a level that is 0,7m or more below the ground surface is preferable. Thereafter, a foundation wall with a CFG base floor is chosen, and hereby the most cost-efficient foundation and base floor combination has been elected.

On the other hand, if the lot already has been acquired, the bedrock level determines the next step. If the bedrock is 0,7m or more below the ground surface, the process continues in the same way as in the case above, where the lot was not yet acquired. If the bedrock however is closer to the surface than 0,7m, the area of the base floor determines the next step. If the base floor area is less than 130m2, a pillar foundation is chosen, whereas a foundation wall with a CFG base floor is to be preferred, if the base floor area exceeds 130m2.

10.5 Discussion

Based on the comparative cost values that have been calculated, it can be concluded that a building lot with bedrock in the surface, in general is a more expensive choice compared to a lot with a bedrock level at 0,7m or more below the ground surface. This implies, that before acquiring a building lot, it is wise to investigate how deep the bedrock level is. The cost of mining the bedrock is the reason why the price is high for all combinations, except for pillar foundations, when the bedrock is present in the surface. For a pillar foundation, however, only channel mining is required if the bedrock is in the surface. Although the pillars are inexpensive, the wooden base floor is so costly, that the pillars alone cannot compensate for a lot with high bedrock and make it attractive from a cost perspective.

The use of a self-supported base floor structure is neither a cost-effective choice on a building lot where ground supported base floor can be used. The self-supported slab increases the investment cost with almost 40%. A ground based base floor is a far more cost-effective solution, even if a separate radon air-ventilation system has to be installed. The raft-slab alternative is only slightly more expensive than the ground supported base floor with a foundation wall. However, there is no economical reason to choose this solution.

Although the pillar foundation may seem like a simple, and therefore cost-effective solution, the comparative cost values imply the unambiguous fact: this alternative is a far more expensive solution compared to the other alternatives. The foundation itself is not very costly, but so is the wooden base floor that is included in this solution. Only if the building lot has bedrock in the surface, it can comprise a competing alternative, for example if the builder wants to save the natural bedrock in its original form, instead of blowing it to pieces.

11 Conclusions

In this study, cost-comparions between different foundation and base floor combinations have been made, in order to find a way to choose the most cost-effective alternative. During the value engineering process, data well-founded by economical calculations has been presented.

It has been proven that bedrock in the surface of the building lot should be avoided, since it increases the cost significantly. If the bedrock is at least 0,7m beneath the surface, the cost of the foundation and base floor unity is the same as if there were no bedrock present. The need for mining activities is the main reason why the surface bedrock represents such an expensive phenomenon.

Furthermore, it has been determined that base floor structures on building lots with firm soil should be ground supported. A self-supported base floor is not an alternative in these cases, as it increases the cost without a cause. Raft-slab foundations and base floors are neither an alternative, as they do not produce the most cost-effective solution.

Pillar foundations are only an alternative if the building lot aleady has been purchased, and the bedrock is in the surface. Otherwise, this is the most costly application, since the wooden base floor is the most expensive base floor that can be used in a small house. Even if it might be the most ecological alternative, it is not compatible with cost-effectiveness.

Another result in the present study, is that there is no real cost-difference between ground frost insulation materials. LCA and EPS have almost the same cost values when comparing them by their functions, even though they are different as materials. When choosing ground frost insulating materials, cost does not have to constitute the main criteria, as the cost does not differ significantly. Instead, the material can be chosen based on what people prefer to use.

Furthermore, it is not cost effective to use polyurethan insulating materials in new buildings, as it is too expensive to be able to compensate for the savings made when the structures are made thinner. In addition, it has it been proven that wood fiber insulating materials are far more cost effective than mineral wool insulation.

The value engineering approach is a very straight forward and simple method for making cost-reductions. However, in order for the VE process to be successful, the function that determine the cost, must be defined in a rather clear and technical way.

12 Further research

The following areas represent directions and suggestions for further research.

- The value engineering approach could be used for basement foundations and pile foundations. This research could show if there are some specific characteristics that should be accounted for when designing and constructing these building parts.
- The value engineering approach could be utilized for all building parts in small houses, such as outdoor walls, roofs etc.
- The value engineering approach could in addition be used to analyze the life-cycle costs versus the investment costs, especially in zero energy buildings and passive houses.
- A value study could offer fruitful data for analyzing different heating methods for buildings.
- Research could be done to investigate costs in already built projects, in order to examine the level of cost knowledge possessed by the designers in the process of defining structural alternatives.

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